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Methodology for energy transition evaluation
Case study: The Balearic Islands, Spain

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Methodology for energy transition evaluation
Case study: The Balearic Islands, Spain

by

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Abstract

Methodology for energy transition evaluation
Case study: The Balearic Islands, Spain

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In a world full of inequalities, energy disparity directly affects development. Developed societies are focused on renewable energies while developing countries are investing in all the different types of energy resources. However, all countries have something in common, the necessity to provide energy to society under the best economic and environmental conditions. This study describes a global methodology for energy transition evaluation applied to the Balearic Islands, Spain. This region is an archipelago 100 miles away from the Iberian Peninsula, well-known as part of the environmental protection program Natura 2000 network. In terms of electricity generation, it is a semi-isolated system where the islands are interconnected and have a connection to the peninsular electric system that covers an average of 22.5% of the energy demand of the archipelago. Almost 95% of the remaining demand is supplied by non-renewable resources. Since European legislation has set goals to promote cleaner energy generation, this document studies all the technically and legislatively viable energy resources in this region and evaluates the trade-offs of transitioning following different strategies. In the first part of the methodology, existing technologies like fossil fuels, onshore wind power, and utility-scale solar are accepted as potential future resources. In addition, new options like microwind, distributed solar PV, hybrid and concentrating solar, and biomass are assessed as viable while others are discarded. During the second part of the analysis, the energy transition in the period 2020 to 2030 is evaluated according to 4 possible scenarios to meet demand: (1) natural gas focus, (2) submarine connection expansion, (3) 50% natural gas/ 50% renewables, and (4) 20% renewables/ 40% natural gas/ 40% submarine connection expansion. The parameters involved in this analysis consider tourism rates, electric vehicle penetration, electricity market prices, and 5 environmental impact indices (global warming, eutrophication, ecotoxicity, particulate matter, and land use). Results show that coal and diesel are responsible for higher environmental impacts, renewables land use could limit their expansion, natural gas use is subject to energy security constraints, and submarine connection expansion, although the best option, could encounter social challenges. In conclusion, this methodology helps to identify trade-offs of different approaches which can be used for technical and strategic analysis.

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Chapter 1. Context

1.1 The World

In a world full of inequalities, energy disparity directly affects development. Energy demand has been growing fast in developing countries in the last few decades. While first world countries enjoy air conditioning, one-third of the world population still uses biomass as their primary source of energy (IEA, 2016). The problem is that everybody wants to live in a first world country. At the same time, we are starting to feel the effects of human exploitation of natural resources. Thus, climate change and resource scarcity play an important role in the current situation of the energy sector. Changes in the environment need to be carefully studied because they could adversely affect the world as we know it today. This is not just because of emissions affecting climate change (e.g. coal power plants) but also because of the direct impact of installations activity (e.g. Wind turbines and migratory birds). Nature presents a unique fascinating self-adjusting environment that must be respected and protected by humans. In addition, global trends such as rapidly changing demographics, fast urbanization, and accelerating technological innovation threaten to increase energy needs and, therefore, environmental stress becoming a cyclical process (Retief, F. et al, 2016). Development implies energy, and energy implies development. On the other hand, we are in an energy transition where conventional energy resources such as coal, natural gas (NG), and nuclear are being replaced by renewable resources like biomass, wind, and solar power followed by progress in sources such as wave and tidal power. Even oil is being threatened by these technologies since electrification of transportation is emerging as an alternative. All this is reflected in private companies shift, with oil and gas companies investing in renewables and the car industry competing to design the most attractive electric vehicle. However, first world countries cannot cause developing countries to slow their development. For this reason, renewable and conventional energy resources will need to coexist for the moment.

Thus, education plays a key role in this changing environment. Everybody has developed an opinion on energy issues: an opinion, most of the time, visceral or guided by biased information. Energy companies (including those focused on renewables) are considered powerful and merciless, led only by capital interests. Yet people ignore how much they rely on them and, therefore, how much society needs them. Energy is the fundamental source of prosperity in humanity's history. For all these reasons, the world problems to be addressed require being open to all energy resources, promoting objectivity when providing information, and supporting access to education. Since the energy transition is on its way but full change is going to take some time due to technical (e.g. battery development), infrastructure (e.g. urban planning), and policy constraints, it is necessary to find the best combination of resources from a social, environmental, and economic perspective. Second, assuming this energy demand will grow rapidly, it is necessary to preserve the accumulated knowledge in all the energy resources we know, and invest in the development of other resources because supplying a growing population and growing energy demand per capita is a great challenge. It is worth mentioning that this point has two important social implications. First, for developing countries, environmental issues are not a priority, the priority is covering basic needs. Second, future energy shortages/crises could result in important violent conflicts. Finally, the lack of understanding of these scenarios by the public and energy companies complicate the situation. People need to know the resources they use, where these resources originate, how these resources are provided and, most importantly, that all resources are finite to a certain degree. Wind is a renewable source but the available land to put wind turbines is not. In addition, energy companies need to accept that the energy panorama is changing and they need to adapt by considering other energy resources, the environment, and the society in their businesses.

Hopefully, the future will be able to cover the growing energy necessities of the world in the most environmentally respectful way. If this does not happen, it is not going to be a matter of energy scarcity or environmental irresponsibility, but about survival in a very unstable world of conflict.

1.2 Spain and the Balearic Islands

Spain is a western European country which relies on non-renewable resources for 60% of its needs (REE, 2016). This includes nuclear, coal, oil, and natural gas for its electricity supply. However, there is a region within the Spanish territory, the Balearic Islands, which presents a unique scenario for several reasons. First, this Mediterranean archipelago partially supplies its electricity needs with a submarine connection with the Spanish peninsula between Sagunto, Valencia and Calviá, Mallorca. Second, the rest of the electricity demand is covered by domestic generation of which 94.4% is non-renewable and 5.6% is renewable production (REE, 2016). Finally, the Balearic Islands (and Spain) are highly dependent on the imports of these energy commodities from other countries: 93.5% for coal, 99.7% for oil, and 99.8% for natural gas (Ministerio de Energía, Turismo y Agenda Digital, 2016). Water supply is also a challenge in this region where there are no permanent rivers and most of the power plants are thermal, therefore, water intensive.

Due to energy security, environmental, and social issues, the Spanish and Balearic governments are looking at other options. Moreover, they are being encouraged by current legislation. At the European Union level, European Directive 2009/28/EC established the energy and climate change goals for the Member States by 2020

(European Union, 2009). In order to reach these goals as a nation, the Spanish government created the Plan de Energías Renovables. From the regional point of view, the Balearic Islands government developed the Plan Director Sectorial Energético de las Illes Balears.

The Balearic Islands have plenty of room for improvement in electricity generation but also in terms of transportation because of the high potential to introduce electric vehicles (autonomy is less problematic in islands). However, since 100% renewable generation is not possible at this technological, infrastructure, and policy point, it is necessary to evaluate other potential combinations of energy resources from social, environmental, and economic perspectives that meet the energy demand of the Balearic Islands.

Chapter 2. Introduction

2.1 The Balearic Islands

2.1.1 Background

The Balearic Islands form an archipelago in the western part of the Mediterranean Sea (see Figure 2.1). The total area is divided into four main islands: Mallorca (3460 km^2), Menorca (702 km^2), Ibiza (541 km^2) and Formentera (82 km^2), and a group of minor islands not considered in this study. Mallorca, the major island, is located in the middle of the archipelago (see Figure 2.2), 160 km away from the peninsular coast (Navarro, A. et al, 1993).

Figure 2.1: Map of the Spanish Peninsula and the Balearic Islands (IGN, 2017)

Figure 2.2: Map of the Balearic Islands (IGN, 2017)

The climate in these islands is classified as Mediterranean with an average temperature of 17 °C, a maximum of 35 °C and a minimum of 0 °C. The average annual rainfall reaches 400 mm/year in Ibiza and Formentera, and 600 mm/year in Mallorca (≈1,000mm in Sierra Norte) and Menorca (Navarro, A. et al, 1993).

The Balearic Islands is an environmental treasure within the Spanish territory where a great part of the land and coast are considered protected areas under the umbrella of Natura 2000 network. This makes it one of the biggest attractions in the Mediterranean Sea. The population of the archipelago is 1,107,220 (INE, 2016) but presents seasonal population growth during summer of around 80% (Gobierno de las Islas Baleares, 2010). Tourism represents 44.8% of the economy of these islands (Exceltur, 2014).

2.1.2 Analysis of the demand

The energy demanded by the Balearic Islands electric system in 2016, which represents a 2% of the total Spanish demand, was 5,832 GWh (see Figure 2.3). This value is 0.6% higher than the demand from 2015 (REE, 2016). Although these factors are not normalized for temperature variations and additional labor, 2016 was a leap year, they are considered valid for the purpose of this study since the changes would be negligible.

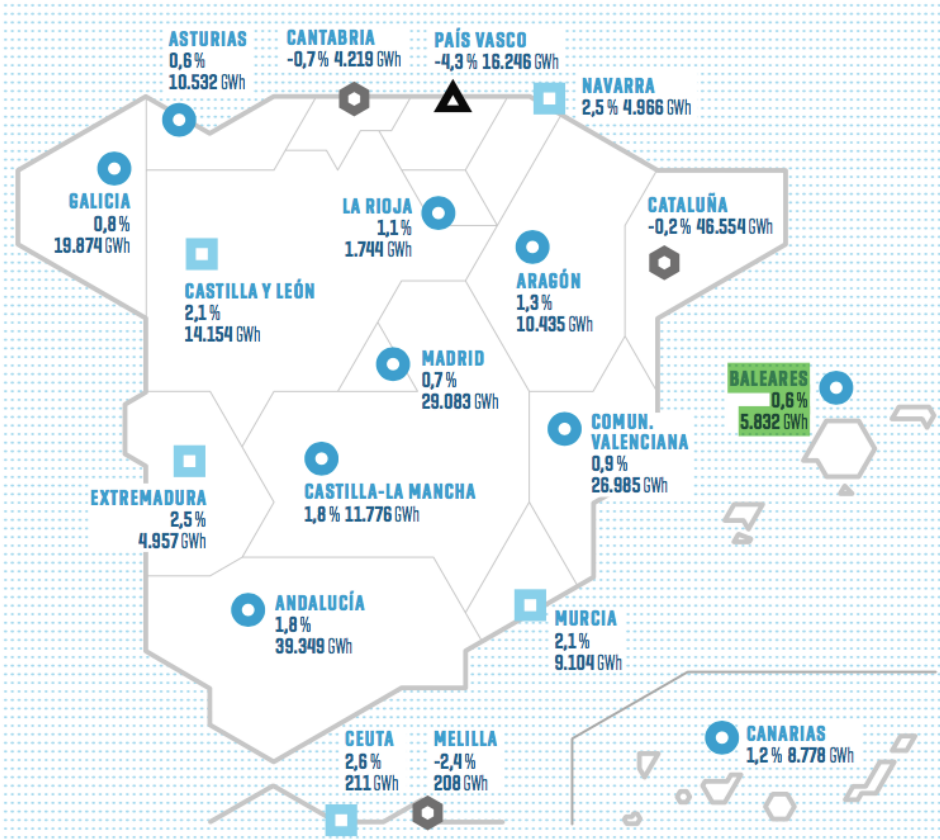

Figure 2.3: 2016 Energy annual demand per region (REE, 2016)

Due to the global economic crisis from 2008, electricity demand decreased substantially in the following years. However, like at the national level, electricity demand started recovering in 2014 (see Figure 2.4).

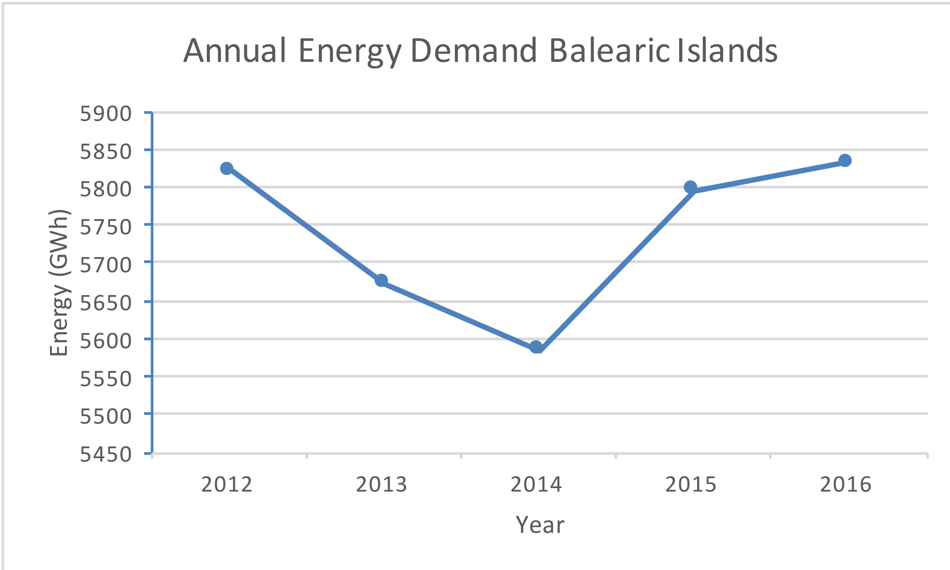

Figure 2.4: Annual Energy Demand Balearic Islands. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

From the analysis of the monthly demand over the last 3 years, it is easy to observe the summer peaks due to seasonal activity. It is also remarkable how energy demand plateaus during winter months probably because of the stabilization of the local population and the mild winters in the Mediterranean climate (see Figure 2.5).

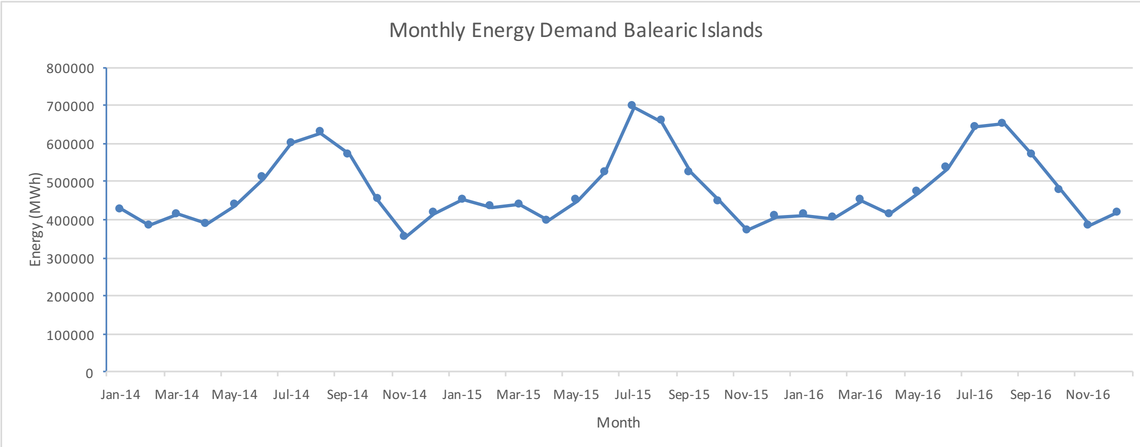

Figure 2.5: Monthly Energy Demand Balearic Islands. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

In 2016, the peak daily energy demand during the summer (June to September) took place on August 4th, 23,168 MWh. The summer peak hourly demand was the same day between 9 and 10 pm. In the winter (October to May), the peak daily energy demand happened on October 5th, 17,453 MWh. However, winter peak hourly demand occurred on October 4th between 8 and 9 pm (REE, 2016).

This demand is partially covered by the submarine connection between the Spanish peninsula and the Balearic Islands inaugurated in 2012. Sagunto, Valencia and Santa Ponsa, Mallorca are connected through a cable 237 km long laid at a maximum depth of 1,485 m (REE, 2015). In 2016, the connection supplied 21.4% of the energy demanded and 30% during hourly peak demand.

Thus, the Balearic Islands electric system is a semi-isolated system with interconnections between the different islands in the archipelago and a connection to the peninsular electric system that covers an average of 22.5% of the energy demand of the archipelago (see Figure 2.6).

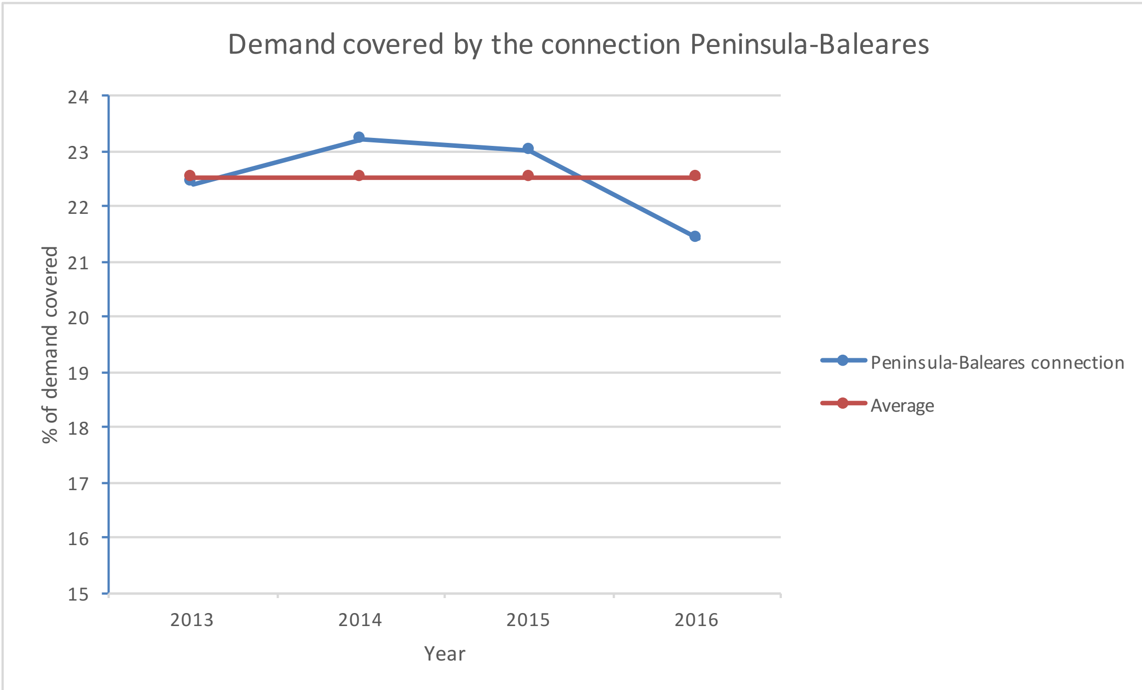

Figure 2.6: Demand covered by the connection Peninsula-Baleares. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

The complementary demand is covered by domestic generation of which 94.4% is non-renewable and 5.6% is renewable production (see Figure 2.7).

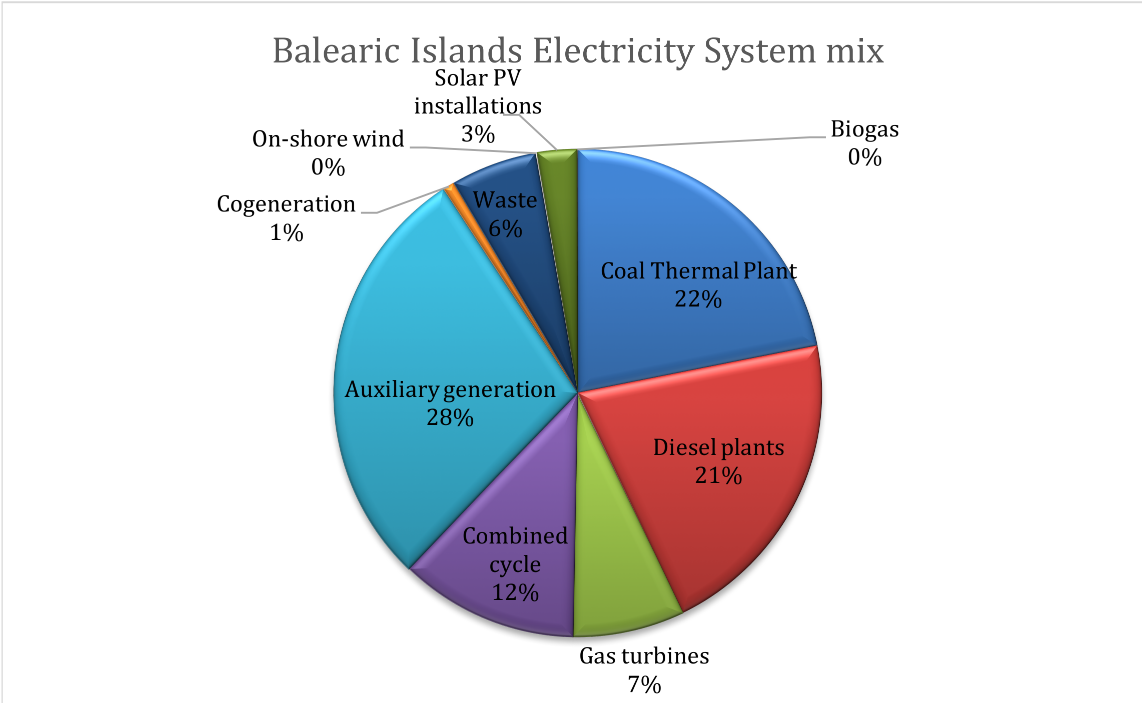

Figure 2.7: Balearic Islands Electricity system mix. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

2.2 The objective

The extreme dependence on fossil fuels to satisfy the Balearic Islands electricity demand (50% oil, 22% coal, and 19% natural gas (REE, 2016)) have important consequences for energy security (93.5% coal, 99.7% oil, and 99.8% natural gas imported) and on the economy of a country and, therefore, a region slowly recovering from a severe economic crisis. In addition, pollution and climate change are major concerns among the population since this archipelago is a natural reserve.

In terms of legislation, the European Directive 2009/28/EC established the energy and climate change goals for the Member States by 2020. These include that 20% of the energy consumption be supplied by renewable energies, 10% of transportation be fueled by renewable resources, a 20% reduction in greenhouse gases emissions and a 20%

increase in energy efficiency (European Union, 2009). In addition, at the end of 2016, the European Commission proposed new legislation including a new directive for the energy policy goals for 2030. This legislation still needs to be approved but considers a 40% reduction of GHG emissions from 1990 levels, that 27% of the total energy consumption be supplied by renewables, and a 27% increase in energy efficiency (REE, 2016). In order to reach these goals, the Spanish government created the Plan de Energías Renovables which reflects European percentages as minimum values and facilitate the integration of renewables in all the Comunidades Autonomas (counties) (IDAE, 2011). From the regional point of view, Plan Director Sectorial Energético de las Illes Balears (Gobierno de las Islas Baleares, 2015) has been modified to provide the needed urban planning directions for the development of renewable energy in these islands.

Thus, the Balearic Islands offer a great example of a region in energy transition. The point of this thesis is to develop a methodology for energy transition evaluation, using the Balearic Islands as a case study.

2.3 METHODOLOGY

The methodology used in the evaluation of the energy transition in the Balearic Islands includes the following steps:

- Background review of the energy panorama in Spain and the Balearic Islands including demand and generation behavior, the country's energy commodity imports, and the related legislation.
- Analysis of the current peninsular and extra-peninsular infrastructures and the electricity market.
- Data gathering about the current situation and the future expectations related to the Balearic electric system. Special focus is on Plan Director Sectorial 2005 and

its modification in 2015 including the restrictions on conventional power plants and the introduction of urban planning instructions for renewable resources.

- Consideration of the current energy resources in Spain and in the Balearic Islands, the potential ones (including resources proposed by the EU, the national and regional governments), and the author suggestions.
- Evaluation of the technical, environmental, and legal viability of these energy resources and consideration (approval or dismissal) for further analysis.
- Design of a model with the "approved" energy resources.
- Evaluation of different scenarios in terms of economics and environmental impact.

Chapter 3. Energy Resources Description

The description of energy resources considers four different sources of information: 1) the Peninsular energy mix because it would be easy and cheap to bring the expertise to the Balearic Islands; 2) the current Balearic energy mix because those sources could potentially be used in the future; 3) the desirable energy mix reflected on the Plan Director Sectorial Energético de las Illes Balears, and 4) the author's suggestions including those resources not considered previously. For the purpose of this thesis, only an enumeration of the resources from each resource is necessary (see Table A.1).

3.1 Peninsular Energy Mix

Thermal power plants are a major constituent of the peninsular energy mix. They include nuclear, coal, gas turbines, cogeneration, combined cycle, waste, biogas, biomass, and geothermal. In addition, different renewable resources are present such as conventional hydro, hydro pure pumping, hydro mixed pumping, marine hydro, onshore wind, solar PV, and concentrating solar thermal (REE, 2016).

3.2 Balearic Islands Energy Mix

3.2.1 Current Energy Mix

Most of the electricity generation in the Balearic Islands come from non-renewable resources including coal power plants, diesel plants, gas turbines, combined cycle, auxiliary generation (fuel with oil and gas), cogeneration, and waste. Only a small percentage of the demand is covered by renewable resources such as onshore wind, solar PV and biogas (REE, 2016).

3.2.2 Desirable Energy Mix

According to the modification of the Plan Director Sectorial Energético de las Illes Balears (Decree 33/2015), the following energy resources are planned to be introduced and expanded for the future electricity supply of the Balearic Islands: distributed solar PV, utility-scale solar PV, microwind, onshore wind, concentrating solar thermal, and hybrid solar PV/thermal (Gobierno de las Islas Baleares, 2015).

3.3 Author suggestions

Some energy resources were not mentioned or were considered as part of a group of technologies in the previous sections and they are worth taking into further consideration. Offshore and concentrating solar PV are feasible technologies widely use in some countries. Marine hydro needs to be considered in its three currently viable forms: ocean wave, tidal range, and tidal/oceanic current. Finally, hydrowind, a combination of hydropower and onshore wind with a precedent used in the Canary Islands, the other Spanish archipelago.

3.4 Summary

The list of energy resources considered in the next chapter to analyze their technical, environmental, and legal viability or possible constraints therefore includes non-renewable and renewable resources. Coal thermal plants, diesel plants, gas turbines, combined cycle, cogeneration, and waste comprise the non-renewable list. While renewables are represented by onshore wind, solar PV installations, biogas, distributed solar PV, microwind power, concentrating solar thermal, hybrid solar PV/thermal, offshore wind, concentrating solar PV, ocean wave, tidal range, and tidal/oceanic current, hydrowind, nuclear, hydro pure pumping, conventional hydro, hydro mixed pumping, biomass, and geothermal.

Chapter 4. Energy Resources Evaluation: approval or dismissal

For the energy resources described in the previous chapter, the ones currently in place were automatically accepted as part of the Balearic Islands potential energy mix to be analyzed with the modeling tool. If any of the non-renewable resources were to be expanded after evaluating them in the modeling tool, the location will be constraint attending to the directions reflected on the Plan Director Sectorial de las Islas Baleares (Gobierno de las Islas Baleares, 2015). In the case of nuclear, this same regulation states that no nuclear development is allowed in the Balearic archipelago (Article 10 - Plan Director Sectorial de Illes Balears). Solar and onshore wind were directly accepted for two reasons. First, there are solar PV and onshore wind installations currently operating and second, one of the goals of the Plan Director Sectorial de Illes Balears is defining the optimum territory for future construction of these installations to promote investments. The viability of the rest of technologies is analyzed below.

4.1 Offshore wind

There are two main limitations to determine the viability of offshore wind installations: seabed depth and wind velocity. In case one of these parameters does not achieve the maximum or minimum, respectively, the construction of offshore wind farms won't be possible.

In the case of water depth, current commercial technology is economically limited to depths of 40 m to 50 m (EWEA, 2013). The bathymetric map of Balearic Sea shows isobaths every 50 m (see Figure B.1). The maximum distance from the coast for a maximum depth of 50 m is 14 km in the Bay of Palma (Instituto Español de Oceanografía, 2001). Therefore, at this stage, offshore wind development would be technically restricted to areas up to 14 km from the coast.

In terms of wind speed, using the National Renewable Energy Laboratory criteria, most wind farms are only profitable for Class 3 wind (6.4 m/s or 14.3 mph). Thus, analyzing the wind speed map of the Balearic Islands for 80 m height (see Figure B.2), the maximum annual average velocity in the archipelago is 7.5 m/s at 80 m over sea level. Considering that turbines will be 30 m tall, application of the power law is needed to extrapolate this value:

$$\frac{V2}{V1} = (\frac{H2}{H1})^{\propto}$$

Since α varies between 0.14~0.16 for "flat land without major obstructions" or the sea, in this case, conservative values were selected.

$$\frac{7.5}{V1} = (\frac{80}{30})^{0.14}$$

As a result, the maximum annual average velocity in the archipelago at 30 m is 6.54 m/s, barely reaching the criterion for minimum profitability (6.4 m/s). In addition, only the north and east coast of Menorca Island present these wind speed conditions (see Figure B.2). Considering, height and depth at the same time, 50 m depth is reached at maximum 6 km away from the coast in this north-eastern Menorca region.

Finally, due to the incorporation of Marine Protected Areas to the official Spanish strategic environmental assessment, an 8-km restriction band from the coast has been established to avoid windfarm development due to seascape impact (Rodríguez-Rodríguez, D. et al, 2016), surpassing the maximum of 6 km in Menorca Island. In conclusion, the development of offshore wind installation in the Balearic Islands is not viable at this point due to environmental and technical restrictions.

4.2 Ocean wave

The analysis of the wave climate in the Balearic Sea in previous studies show that this is a high variability area due to complex storm patterns, orography, and fetch duration (Ponce de León, S. et al, 2015). In contrast, Wave Energy Converter (WEC) systems viability relies on high but also permanent energy locations.

As a result, from the analysis of wave height, wave period, and all their possible combinations, the highest wave power potential in the Balearic Islands takes place in the north part of Menorca Island, while north and east sides of Mallorca also offer a certain potential for WEC. Potential decreases in southern islands due to changes in wave direction and sheltering effect. The lowest average energy flux value in the archipelago correspond to the Bay of Palma, 2.5 ± 0.3 kW/m while northern Menorca offers the highest value, 9 ± 2.5 kW/m. However, these values vary significantly during the year for all the locations, increasing by five times the mean value 15% of the time from November to February but reaching the average value only 2% of the time during summer months. Thus, it could be considered that energy flux is six times larger during winter compared to summer (Ponce de León, S. et al, 2015).

A review of the currently available technologies indicates that only one is currently an option for wave power generation: Pelamis. Other possibilities such as Archimedes waveswing, Aquaboy, Limpet, and Oyster were discarded since they are still at the prototype stage. Under Pelamis specifications (Pelamis, 2017), areas with annual average energy flux over 15 kW/m are eligible to produce electricity at competitive prices. Since the maximum potential value in the Balearic Islands (9 ± 2.5 kW/m) is below this value, the Balearic Sea is not considered a potential source.

In conclusion, due to large temporal and spatial variability and low values of energy flux, wave power is not suitable as an energy resource for the Balearic Islands.

4.3 Tidal range

The main parameter to consider for tidal range power is the range difference between tides. For this energy resource to be feasible, there must be a acceptable range between low and high tide. The Ocean Energy Council establishes 7 m as the minimum tidal range to be profitable and technically viable by assuring enough head of water for the turbines (Ocean Energy Council, 2017).

In the case of the Balearic archipelago, the analysis of the daily variations through 2016 and 2017 show that variations in the four islands range from -0.1m during low tide to 0.1m during high tide (Tablademareas, 2017).

Since 0.2 m is the total tidal range for the Balearic Sea and the minimum required by the current technologies in use is 7 m, tidal power in this region can be considered negligible and, therefore, not viable.

4.4 Biogas

The two main sectors to be considered as sources of organic products for biogas production are industry and agriculture. In addition, waste from these sources can be divided into several groups to facilitate the analysis of their potential. Thus, the sources considered include food industry (animal and vegetal) waste, cattle dung, biofuel industry derivatives, food store discard, and services industry (hotel and restaurants) refuse (IDAE, 2011).

Biogas Source	Available Potential (ktep/year)
Food industry	3.97
Cattle dung	6.06
Biofuel industry	0.04
Food store & services industry	1.28
TOTAL	11.35

Table 4.1: Balearic Islands biogas production potential. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from Informe de sostenibilidad ambiental del Plan de Energías Renovables 2011-2020 (IDAE, 2011)

Although the potential of biogas production in the Balearic Islands seems low, other sources such as urban organic waste, sewage water, and landfill organic products could become new sources in the future.

In any case, since the uses of biogas in terms of electricity generation are inclusion in the natural gas supply system (after increasing methane content to 96%) and combustion in cogeneration plants, this energy resource can be used in already existing power plants. In conclusion, due to low levels of biogas generation and few viable alternatives for using this fuel to produce electricity in current installations, no pure biogas power plants are considered.

4.5 Biomass

In order to evaluate the potential biomass power in the Balearic Islands, an analysis of the present biomass needs to be conducted. Biomass sources are classified as available and removable. Available biomass considers biomass valuable to be harvested but unacceptable for the timber industry. Removable biomass is the part of available biomass that is economically viable to be removed according to current prices. The different types of biomass and their available quantities for the Balearic Islands are presented below (see Table 4.2).

Biomass Source	Available (ton/year, 45% moisture content)
Full tree	51,551
Woody biomass eligible to be planted in forest land	8,025
Woody biomass eligible to be planted in agriculture land	47,555
Herbaceous agriculture waste	113,942
Woody agriculture waste	405,250
Timber harvest and industry waste	9,126

Table 4.2: Balearic Islands biomass sources available portion. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from La biomasa en España. Disponibilidad de recursos PER 2011-2020 (Cabrera Bonet, M., 2013)

To determine the removable portion, economic factors need to be considered from the biomass supply and the electricity generation perspective. On the biomass supply side, production and extraction direct costs and average transportation costs were considered. In the case of electricity generation, the initial investment for the construction of the biomass power plant, operation costs, and price of biomass for a certain capacity installation for 7,500 hours of operation determine what an energy producer would be willing to pay for this fuel (PER, 2011). Contemplating these two factors and a spread use of power plants of 10 MW, the removable portion for the Balearic Islands can be calculated (see Table 4.3).

Biomass Source	Removable (ton/year, 45% moisture content)
Full tree	1,283
Woody biomass eligible to be planted in forest land	3,440
Woody biomass eligible to be planted in agriculture land	20,729
Herbaceous agriculture waste	76,196
Woody agriculture waste	129,430
Timber harvest and industry waste	1,315
TOTAL	232,393

Table 4.3: Balearic Islands biomass sources removable portion. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from La biomasa en España. Disponibilidad de recursos PER 2011-2020 (Cabrera Bonet, M., 2013)

The total removable biomass is 232,393 t/yr. However, 24,169 t/yr are potential plantations that will need to be introduced by developing this industry sector in terms of stakeholders, program planning, and biomass management but they are not currently in place. In addition, 76,196 t/yr correspond to herbaceous agricultural waste, very abundant but also subject to changes in parallel markets making them difficult to be considered as a reliable source for electricity generation.

Thus, applying the worst-case scenario by excluding these sources of biomass, the final biomass that could be used in the Balearic Islands as an electricity source is 132,028 t/yr (45% moisture content). Finally, considering a 10 MW pure biomass power plant requires 130,000 tons of biomass (44% moisture content) (NuGen Engineering Ltd., 2010), the Balearic Islands could develop biomass power for a maximum of 10 MW.

4.6 HYDROELECTRIC POWER

The Balearic Islands do not have any continuous hydraulic resources. This archipelago has temporary torrents but are dry most of the year, with very variable volumes and directly dependent on heavy rains (Gobierno de las Islas Baleares, 2015). Due to these extreme variations, the available surface water resources in the archipelago are present in Mallorca Island in the form of three dams, Cúber, Gorg Blau, and Estany de Mortitx (see Figure 4.1) with an average availability of 6.9 hm^3/year (Gobierno de las Islas Baleares, 2015).

Figure 4.1: Dams in the Balearic Islands (Gobierno de las Islas Baleares, 2015)

Due to these irregularities in surface water supply, construction of new dams is automatically discarded. In addition, lack of information about Estany de Mortitx suggests its contribution is negligible compared to Cúber and Gorg Blau dams.

Both Cúber and Gorg Blau dams are located in the Tramuntana Mountains near each other. They supply the biggest city in the Balearic Islands, Palma. Their dimensions and other technical aspects need to be considered to assess their hydroelectric potential (see Table 4.4). There is a precedent of hydroelectric power generation in this area as there are records of a power plant from 1906 in Cals Reis.

Dam	**Gorg Blau**	**Cúber**
Height over foundation	43.18 m	26.00 m
Height over riverbed	38.18 m	21.50 m
Maximum dam height	610.00 m	747.30 m
Riverbed surface	7.92 km^2	7.32 km^2
Dam surface	59.90 Ha	59.30 Ha
Dam capacity	7.36 Hm^3	4.64 Hm^3

Table 4.3: Dam characteristics. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from Embalses (EMAYA, 2017)

However, before considering technical viability, environmental constraints need to be analyzed. In 2007, Tramuntana Mountains were declared natural reserve (paraje natural) by the Balearic Islands government (see Figure 4.2) (Gobierno de las Islas Baleares, 2007).

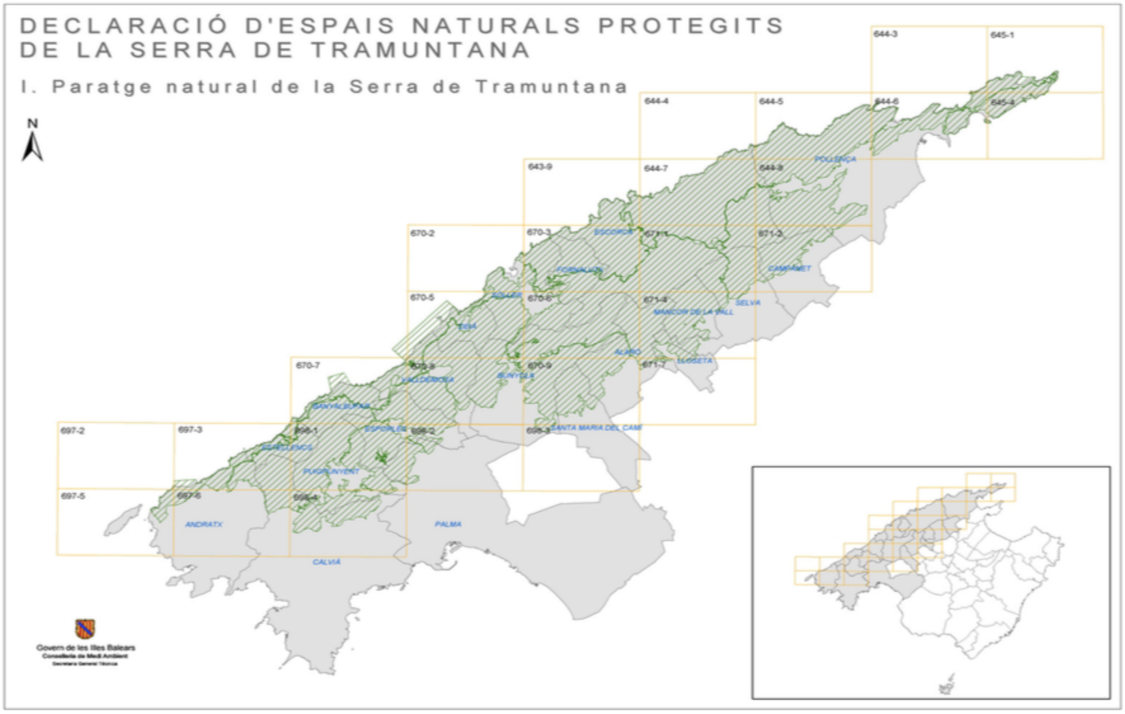

Figure 4.2: Sierra de Tramuntana: Natural Reserve (Gobierno de las Islas Baleares, 2007).

Considering the definition of natural reserve reflected in Anuario Estadístico de Andalucía, these regions are protected to facilitate the preservation of orography and biodiversity; they require intensive management and some activities are restricted or banned. Among the banned activities, the Balearic Islands government include the destruction of mineral and rocks, modifications of the orography, and development of new roads or paths; all of them directly opposed to the potential construction of a hydroelectric power plant.

Taking into account that both dams, Cúber and Gorg Blau, are part of this natural reserve (see Figure 4.3 and Figure 4.4), the development of a hydroelectric power plant associated with these dams is not viable.

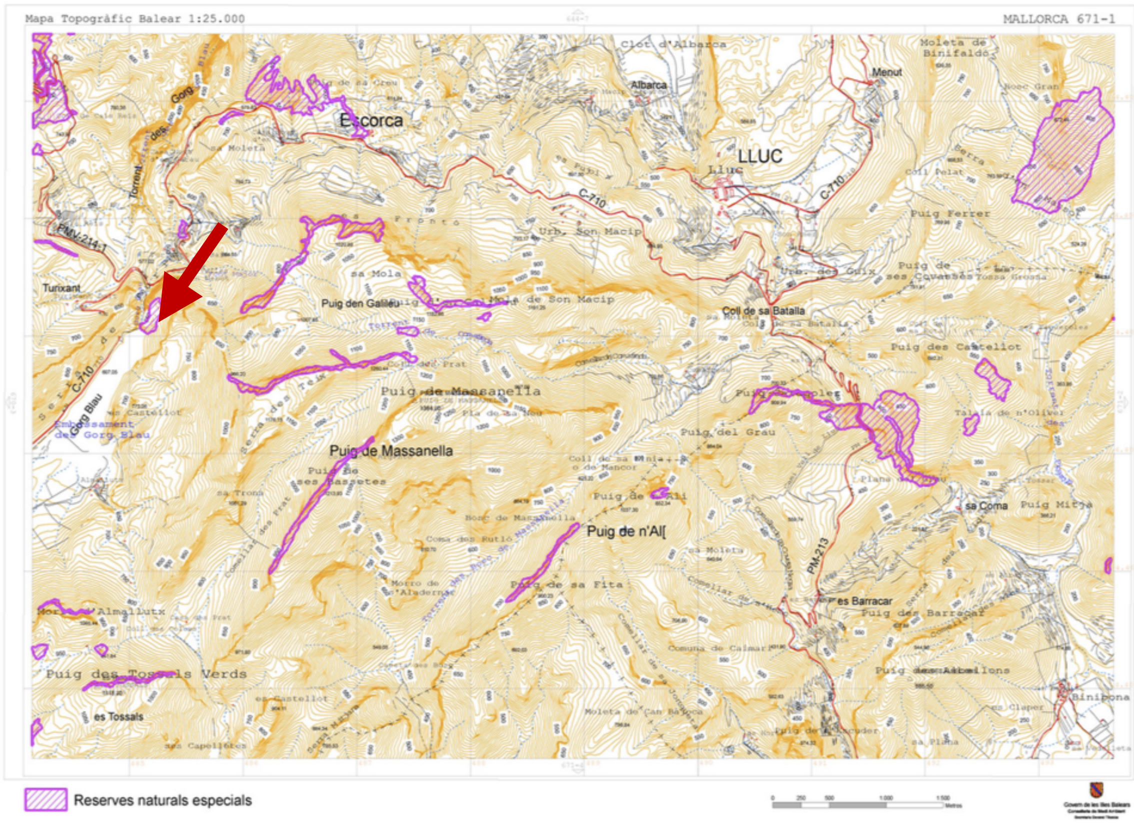

Figure 4.3: Gorg Blau dam located in the Natural Reserve (Gobierno de las Islas Baleares, 2007).

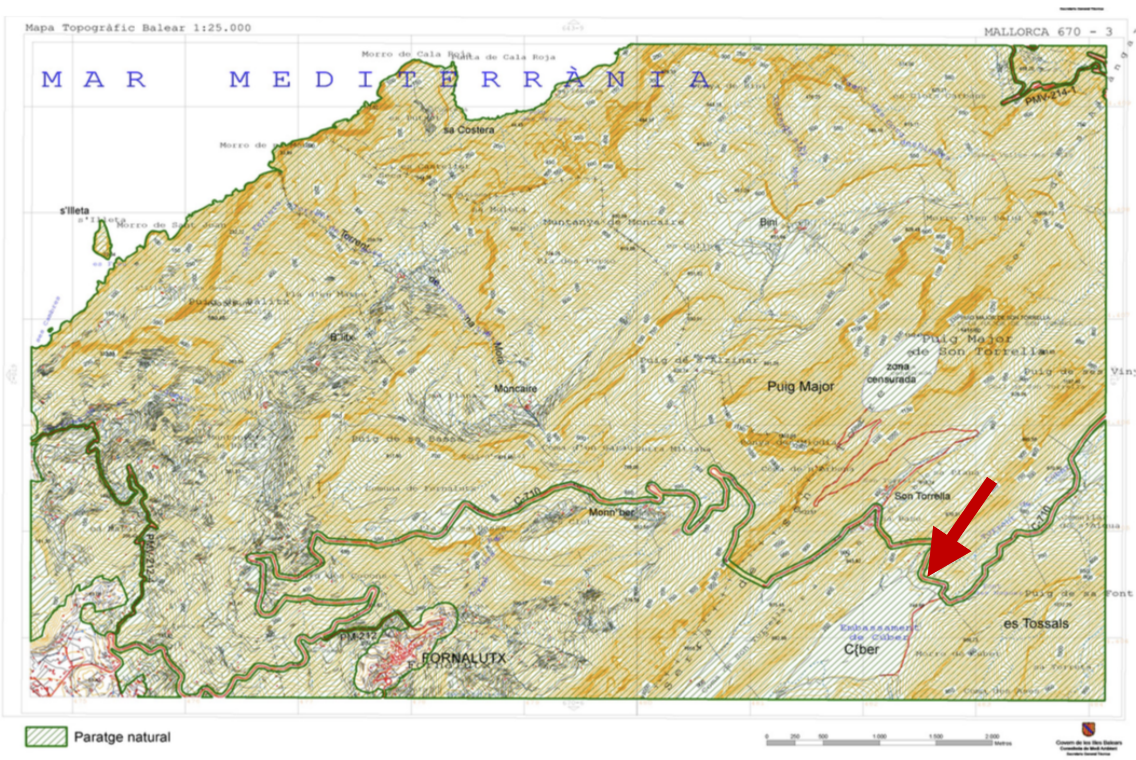

Figure 4.4: Cúber dam located in the Natural Reserve (Gobierno de las Islas Baleares, 2007).

In addition, Cúber dam is considered by the Natura 2000 network, a Special Area of Conservation (SAC), Site of Community Importance (SIC-LIC), and Special Protection Areas for birds (SPA-ZEPA). Gorg Blau is in some parts less than 400m away from these areas (see Figure 4.5).

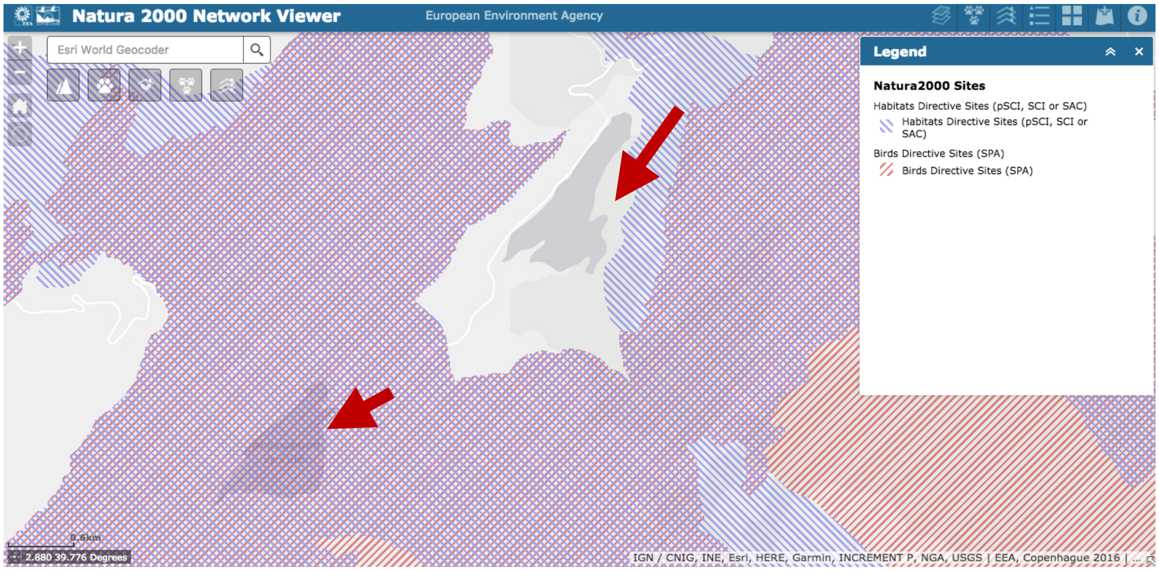

Figure 4.5: Cúber and Gorg Blau dams in Natura 2000 Network Viewer (EEA, 2016)

Thus, due to the ecological and diversity value of this area, construction of big scale hydro plants is not viable. In addition, a decrease in hydraulic resources and an increase in interannual variability is expected to happen especially in Guadiana, Canary Islands, Segura, Júcar, Guadalquivir, and Balearic Islands (MARM, 2005), challenging the technical viability of future projects.

It is worth mentioning that smaller projects, such as, microhydro generation by substituting energy dissipators downstream for turbine-generator systems could be considered since they wouldn't disrupt these protected areas. However, these projects are not economically feasible with current technology (Álvarez Llabre, F., 2014).

Finally, hydro pure pumping and hydro mixed pumping were also rejected as potential resources for the Balearic Islands since they are not feasible without the development of conventional hydro installations.

4.7 Oceanic current

The site requirements for tidal current power include a large area of fast-moving water, even seabed to avoid turbulence and losses, and a minimum depth to allocate large turbines, therefore, a big scale project can be developed making this technology cost-effective (Fraenkel, P.L. 2002).

One of the main factors that produce oceanic current is the variation between tides. Thus, the ideal kinetic energy for oceanic power operation is created by a height of 15 m at low tide and between 40 to 50 m at high tide. Low tide depth accommodates the rotor. Since tidal variation in the Balearic Sea is 0.2 m (Tablademareas, 2017), the potential of this technology is reduced significantly. In addition, 50 m of depth corresponds in most areas with the 8km restrictive band declared as Marine Protected Areas (see Figure B.1). Although this exclusion zone was created for offshore wind farms, it can be assumed that it could be applied to tidal current since the exclusion is due to environmental impact and obstruction to other uses of the sea (Rodríguez-Rodríguez, D. et al, 2016). Lastly, a great part of the coast in the Balearic Islands are considered by the Natura 2000 network, a Special Area of Conservation (SAC), Site of Community Importance (SIC-LIC), and Special Protection Areas for birds (SPA-ZEPA), limiting the potential development (see Figure 4.6).

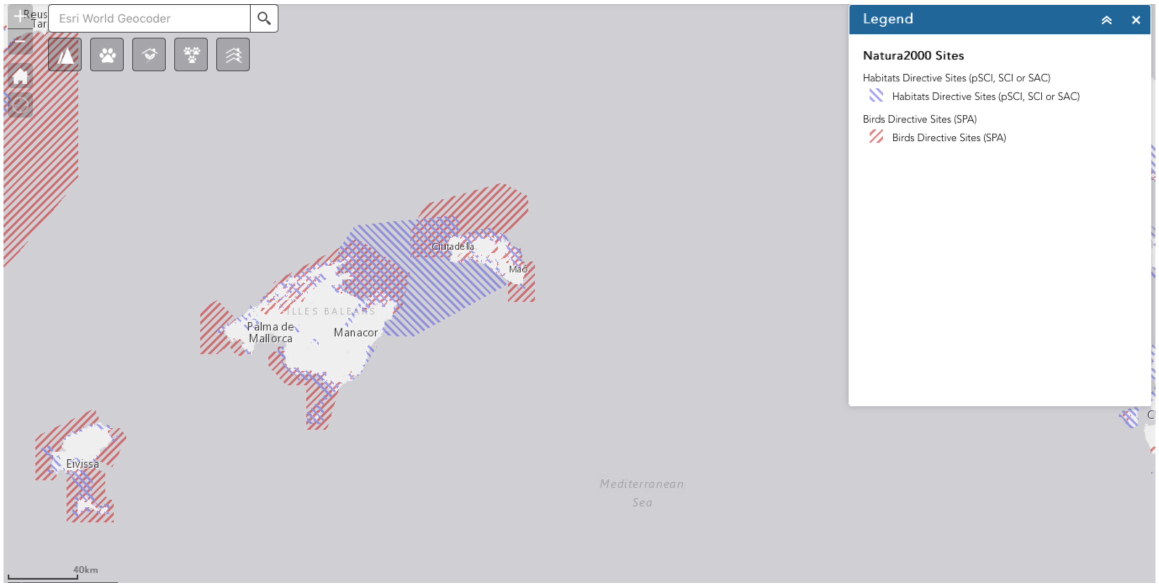

Figure 4.5: Balearic Islands in Natura 2000 Network Viewer (EEA, 2016)

However, there are other factors that affect oceanic currents such as, Coriolis, thermal changes, and salinity variations. In the case of the Balearic Islands, the North current is a thermohaline current 30 to 50 km wide and 300-400 m deep with a maximum velocity of 0.3-0.5 m/s reached on the surface and in the center of the current (Rubio Company, A., 2006). As a result, from the circulation of this current, a secondary current is created, the Balearic current which is shallower and slower. Since thermohaline current is less powerful than tidal current but create a more constant flux, a lower peak velocity of 1.2-1.5 m/s is needed to be economically viable (Fraenkel, P.L. 2002). Nevertheless, as can be deduced from the data presented, minimum peak velocities cannot be reached in the Balearic Sea.

In conclusion, due to physical and environmental constraints, oceanic current is not likely to be a form of power for the future electricity supply of the Balearic archipelago.

4.8 Hydrowind

Gorona del Viento is a hydrowind installation in El Hierro island in the Canary archipelago. The system integrates a wind farm, a hydroelectric installation, and a pumping system. Thus, the wind installation supplies the grid and, simultaneously, the pumping system as a storage solution. The hydroelectric power plant generates electricity using the pumped water as the energy source, ensuring electricity supply (REE, 2016).

A version of this installation could be created in the Balearic Islands if a reversal hydro power plant could be built between Cúber and Gorg Blau dams complemented with new wind power generation. However, environmental constraints hinder this possibility.

4.9 Geothermal

The total geothermal resources in the Spanish territory with a theoretical potential for electricity generation is 2,667 MW (1,695 MW from medium enthalpy resources, 100-150°C, and 972 MW from high enthalpy resources, >150°C) (Arrizabalaga, I. et al., 2015). However, none of these geothermal resources are in the Balearic archipelago.

There is some potential in Mallorca Island (see Figure 4.6) but as low-temperature geothermal resources (30-100°C). Low-enthalpy reservoirs (<100°C) use closed and open loop systems to provide direct heating but not for electricity generation (Colmenar-Santos, A. et al., 2015).

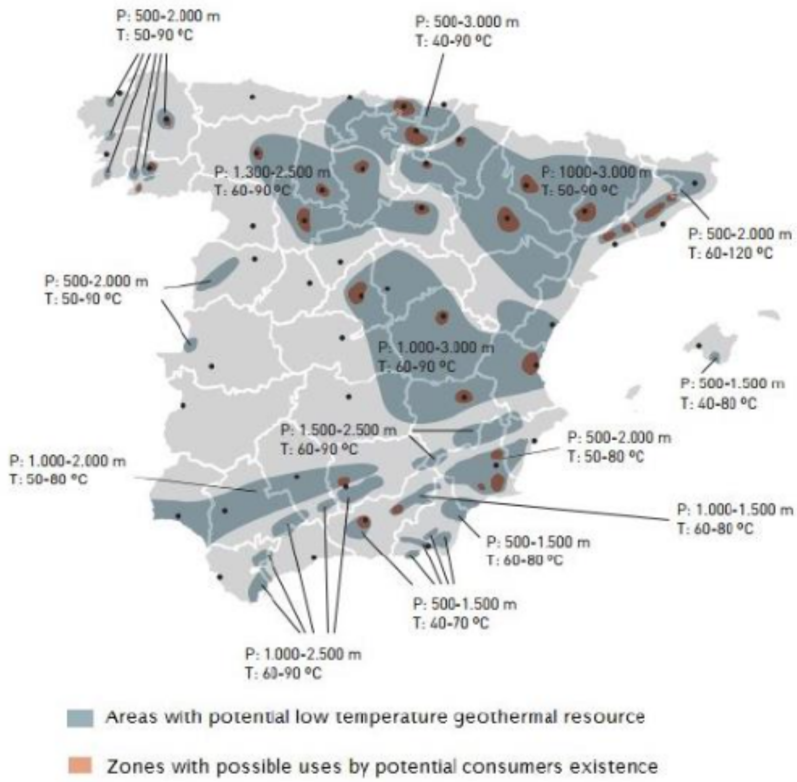

Figure 4.6: Map of low-temperature geothermal resources and zones with good potential for resource exploitation (IDAE, 2010)

Recent studies have identified potential areas in Costitx and Llucmayor. Costitx presents temperatures around 50°C. In the most anomalous and therefore more geothermally active area, Llucmayor, three different geothermal reservoirs were found with temperatures of 60°C, 70°C and 80°C, respectively. Since the area with more theoretical potential does not reach the minimum 100°C to become a probable resource for geothermal electricity generation, geothermal power cannot be included in the analysis of potential energy mix in the Balearic Islands.

4.10 FINAL ENERGY RESOURCES EVALUATED

As a result of the previous analysis and considerations, a final list of energy resources to be evaluated is identified and will be used in the following chapter as part of the input data for the web-based modeling and simulation tool. This list includes coal power plants, natural gas turbines, cogeneration, diesel power plants, combined cycle, and waste generation among the conventional resources. In addition onshore wind, utility-scale solar PV, concentrating solar thermal, concentrating solar PV, microwind, hybrid PV/thermal, distributed solar PV, and biomass from the renewable options are considered.

Chapter 5. Insight Maker

Insight Maker is a web-based, general-purpose simulation and modeling tool that will be used for the representation and evaluation of the different scenarios considered in this study. Insight Maker is a free, user-friendly tool that encompasses three different approaches in modeling development (System Dynamics, Agent-Based Modeling, and imperative programming) in a single framework. This tool presents an embedded graphical model construction interface that runs on the users' devices. Insight Maker is an accepted application that is used worldwide and has a significant number (20,000) of registered users (Fortmann-Roe, S., 2014).

5.1 Tool set-up

Since the purpose of this study includes the evaluation of different scenarios for future energy mixes in the Balearic archipelago, the first step is the time period to be considered. Thus, the selected time frame would be from 2020 until 2030. 2020 was considered a better starting date instead of the present because it provides time for infrastructure to be developed or, at least, planned. The final date is defined by the deadline of the future more restrictive legislation from the European Union, as previously explained (see Chapter 2).

In terms of the input data to build the model, Insight Maker will be structured in three sections: technical, economic, and environmental. The first section will address the options for the energy mix and the forecasted demand. The last two sections (economic and environmental) will use the results needed to compare the scenarios from an economic and environmental perspective.

5.1.1 Section 1: Technical considerations

5.1.1.1 Generation

In this section, all technologies identified in Chapter 4 are described in the context of single units of that technology. The submarine connection is added to this list as an expansion of the energy provided by this cable. The type of unit depends on the nature of the technology. These units are the factors that will determine the mix (see Table 5.1).

The unit power capacities associated with each unit were determined from current installation capacity ranges in Spain (REE, 2016), international institutions (SEIA, 2017; NREL, 2017; Biomass Power Association 2017), industry (Enair, 2017), and experts' observations (see Table 5.1).

The capacity factor of each technology was calculated from historical data by dividing actual generation by capacity (see Table 5.2). Most of the data was collected for non-peninsular regions (islands, Ceuta, and Melilla). Thermal solar was the only case where non-peninsular data was not available, therefore, the author decided to use peninsular values. Some simplifications were also made. Concentrating solar PV was assigned the same capacity factor as utility-scale solar PV. Microwind and distributed solar PV were considered to have the same capacity factor as onshore wind and utility-scale solar PV, respectively. For hybrid PV/thermal, concentrating solar thermal and utility-scale solar PV factors were considered but the limiting value (utility-scale solar PV) was finally chosen. Lastly, the capacity factor for the submarine connection was considered 1 since it does not apply by definition (see Table 5.1).

Technology	Unit	Unit Power Capacity – UPC (MW)	Capacity Factor - CF
Coal	Power plant	30	0.56
NG turbines	Power plant	30	0.31
Cogeneration	Power plant	30	0.09
Onshore wind	Wind turbine	1	0.29
Concentrating solar thermal	Power plant	5	0.25
Concentrating solar PV	Solar panel	0.025	0.19
Microwind	Wind turbine	0.003	0.29
Diesel	Power plant	10	0.31
Combined cycle	Power plant	10	0.24
Waste	Power plant	10	0.40
Utility-scale solar PV	Power plant	1	0.19
Hybrid PV/thermal	Solar panel	0.007	0.19
Distributed solar PV	Solar panel	0.002	0.19
Biomass	Power plant	2	0.23
Submarine connection	-	100	1.00

Table 5.1: Unit, unit power and capacity factor definition. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from sources mentioned in text

Technology	Capacity Non-peninsular systems (MW)	Capacity*8760 (GWh)	Energy generated (GWh)	Capacity Factor
Coal	468.40	4,103.18	2,303.77	0.56
Diesel/gas	2,490.06	21,812.93	6,764.55	0.31
Combined cycle	1,722.15	15,086.03	3,574.25	0.24
Onshore wind	156.27	1,368.89	399.46	0.29
Utility-scale solar PV	244.30	2,140.03	397.94	0.19
Concentrating solar thermal	2,299.43	20,142.98	5,060.14	0.25
Biomass	5.50	48.16	11.00	0.23
Cogeneration	44.09	386.25	34.70	0.09
Waste	76.97	674.24	271.31	0.40

Table 5.2: Capacity factors calculation. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

Thus, total generation is modeled using the following equation:

$$Actual\ Energy\ Produced\ \left(\frac{MWh}{yr}\right) = 24 \times 365 \times \sum_{i=1}^{15} (\#unit_i \times CF_i \times UPC_i)$$

Where:

#unit is the number of units of a certain technology

CF is the related capacity factor

UPC is the capacity of each unit

Using the input variables, Actual Energy Produced (MWh/year) = 24*365*[#Coal pp built *0.56*30 + #NG Turbines pp built *0.31*30 + #Cogeneration pp built *0.09*30 + #Onshore wind turbine built *0.29*1 + #Concentrating Solar Thermal pp built *0.25*5 + #Concentrating Solar PV pp built *0.19*0.025 + #Microwind turbines built *0.29*0.003 + #Diesel pp built *0.31*10 + #Combined cycle pp built *0.24*10 + #Waste pp built *0.40*10 + #Utility-scale Solar PV pp built *0.19*1 + #Hybrid PV/thermal solar panels built *0.19*0.007 + #Distributed solar PV panels built *0.19*0.002 + #Biomass pp built *0.23*2 + #Submarine connections *1*100]

Regarding the number of units available for each technology, some of them are limited by fuel availability (biomass) or development restrictions (conventional power plants, solar, and wind). However, the only technology that presents a clear limitation is biomass generation with 10 MW (see Chapter 4). For non-renewable resources, as reflected on the Plan Director Sectorial Energético de las Islas Baleares, the development of conventional power plants (coal, NG turbines, diesel, combined cycle, cogeneration, and waste) is limited to the expansion of current installations and new development is restricted to Ca's Tresorer area. In addition, NG has priority over other types of fuels. However, no limitations have been clearly established in terms of capacity neither in the expansion of current installations or new ones (Gobierno de las Islas Baleares, 2015). In terms of waste generation, the Plan Director Sectorial Energético de las Islas Baleares, restricts the development of these plants to regional planning, however, in other sources the Council of Mallorca considers the possibility of increasing the capacity of the major waste plants (Council of Mallorca, 2011). Finally, the restrictions for wind and solar in the Plan Director Sectorial Energético de las Islas Baleares could be better characterized as guidelines and recommendations because they don't present any limitations.

5.1.1.2 Demand

Simultaneous with generation, the model computes the energy demand based on Spanish population growth, tourism activity, and penetration of electric vehicles in this archipelago.

Since the estimated population growth is negligible (see Figure 5.1), it can be considered that the base demand is constant, only increased by the introduction of EV and the variation in tourism activity. Note that increments in Figure 5.1 are 0.2%.

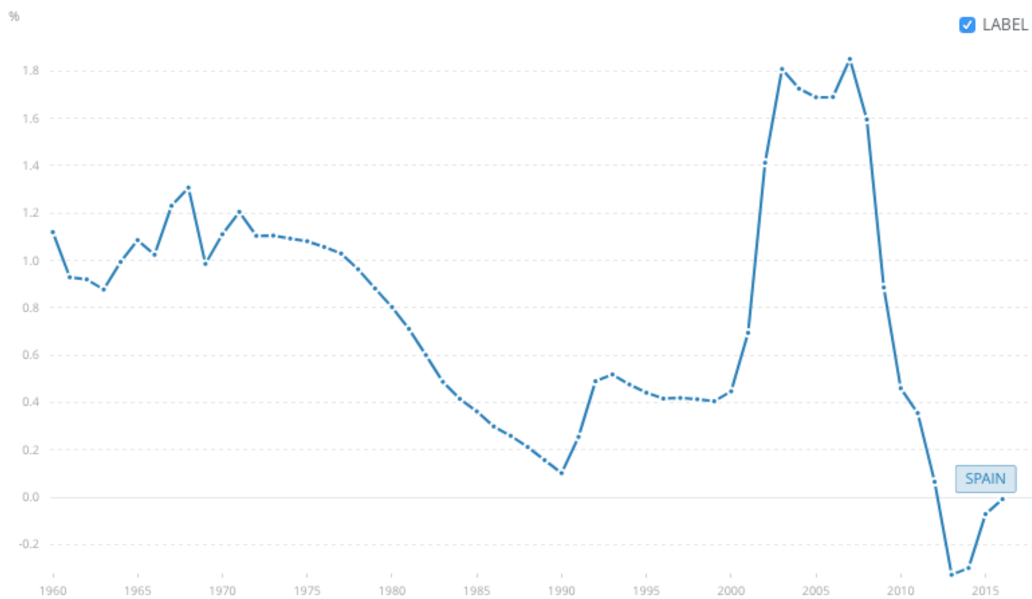

Figure 5.1: Population growth (annual %) in Spain (The World Bank, 2017)

In terms of EV penetration considerations, legislative decisions are recent but progress has been made in the last few years and it is expected to continue, therefore, affecting future energy demand. In 2013, the Dirección General de Industria y Energía proposed a pilot project for the introduction of electric vehicles in the Balearic Islands to the Ministry of Industry. The project included 2,000 public and private charging points with associated parking and would involve car rental companies (Gobierno de las Islas

Baleares, 2015). In 2014, the Instituto para la Diversificación y Ahorro de la Energía and the Balearic Islands government signed a collaboration agreement for the development of a charging point network in the islands (MOVELE Baleares). The project would have a duration from March 14, 2014 to March 14, 2020 (Gobierno de España, 2014). Thus, the outlook provided by the Dirección General de Industria y Energía reflects negligible penetration of EVs during the construction of the charging point network followed by a progressive increase from that point on (see Figure 5.2). The trend has been projected to the future to analyze the penetration until 2030 (see Figure 5.2 and Table 5.3). For the purpose of this study, the number of charging points stays constant.

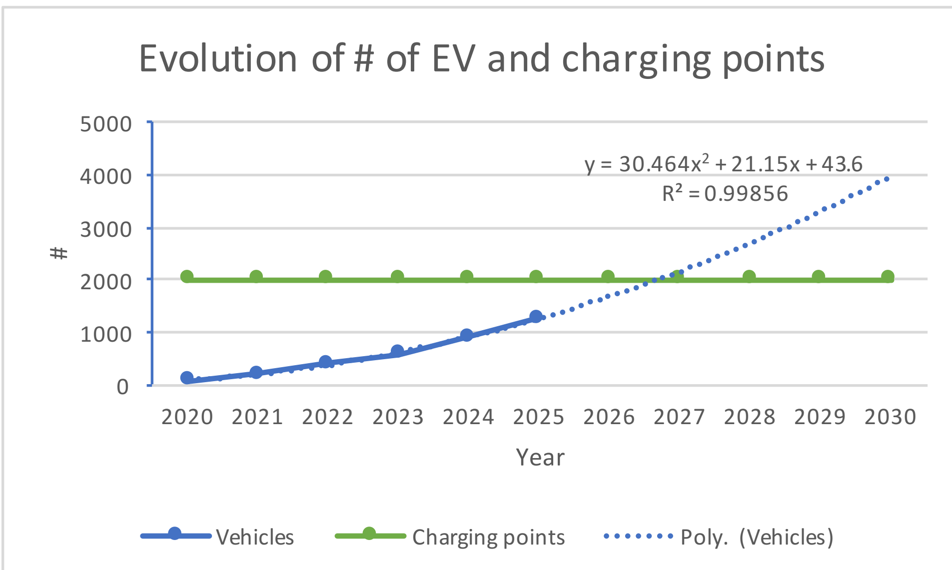

Figure 5.2: Evolution and projected evolution of number of electric vehicles and charging points in the Balearic Islands. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from Energías Renovables y Eficiencia Energética en las Islas Baleares: Estrategias y líneas de actuación (Gobierno de las Islas Baleares, 2015)

Year	# Charging points	# Electric Vehicles
2020	2000	91
2021	2000	205
2022	2000	409
2023	2000	591
2024	2000	909
2025	2000	1,273
2026	2000	1,684
2027	2000	2,162
2028	2000	2,702
2029	2000	3,302

Table 5.3: Evolution and projected evolution of number of electric vehicles and charging points in the Balearic Islands. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from Energías Renovables y Eficiencia Energética en las Islas Baleares: Estrategias y líneas de actuación (Gobierno de las Islas Baleares, 2015)

Considering the average consumption for an electric vehicle with the current technology is 34 kWh to travel 100 miles, or 160km, (US Department of Energy, 2017) and the average annual mileage for personal vehicles in the Balearic Islands is 11,370.6 km/yr (INE, 2008), the average annual energy consumption for an electric vehicle in the Balearic Islands can be calculated to be 2.4 MWh/yr. Thus, the contribution of EV penetration to the annual demand calculation would be represented by the multiplication of the quantity of EVs by the average annual energy consumption for an electric vehicle in the Balearic Islands.

The final factor considered in the analysis of demand is the tourism activity growth. Information about tourists reaching the islands by plane, cruise, and ferry in the period 2012 and 2016 was gathered (Gobierno de las Islas Baleares, 2017) in order to develop a projection for 2020-2030 (see Figure 5.3).

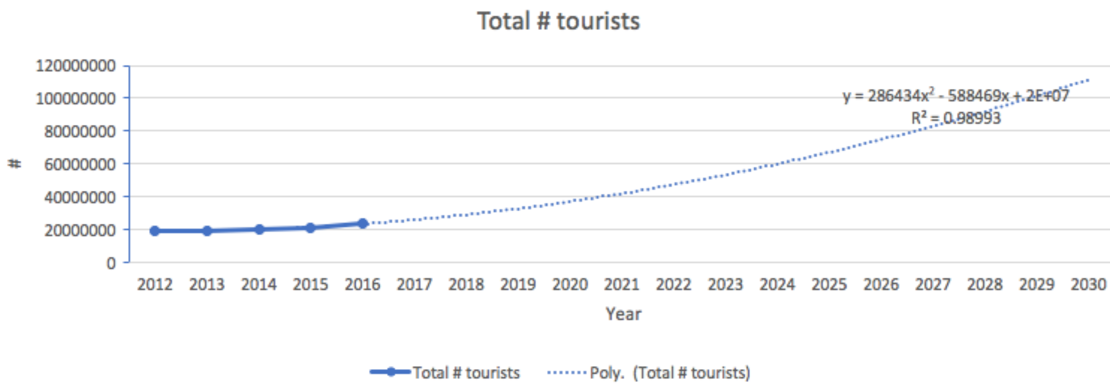

Figure 5.3: Analysis of tourist growth activity. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El turismo en las Islas Baleares Anuario 2016 (Gobierno de las Islas Baleares, 2017)

Given this projection, tourist arrival data can be determined and the growth rate can be calculated. The annual growth rates referred to the previous year in the period 2020-2030 vary between 10% to 14% maintaining to a degree the growth rate from 2015 to 2016 (11%). However, for the purpose of this study, the rates will be referenced to the starting date (2020) since the model does not consider cumulative values (see Table 5.4). In addition, these rates will automatically be applied to the baseline demand since tourist growth rate will be considered to grow energy demand in the same proportion.

Time Period	Growth Rate (%)
2021/2020	13
2022/2020	27
2023/2020	43
2024/2020	60
2025/2020	79
2026/2020	100
2027/2020	121
2028/2020	145
2029/2020	170
2030/2020	196

Table 5.4: Tourism activity growth rates referred to starting date (2020). Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El turismo en las Islas Baleares Anuario 2016 (Gobierno de las Islas Baleares, 2017)

Finally, as mentioned above, the baseline demand will be considered constant. However, the available data is from 2016 (see Chapter 2) so the values have been adjusted to 2020 (starting date of the model) by applying the projected tourism growth rates from 2016 to 2020. Note that no EV demand is considered because it is classified as negligible until 2020.

$$\text{Energy } Demand_{2020}\ (\text{GWh}) = 5{,}832 \text{ x } 1.14 \text{ x } 1.12 \text{ x } 1.12 \text{ x } 1.13 = 9{,}424 \text{ GWh}$$

Thus, the energy demand evolution is modeled using the following equation:

$$Demand = Baseline + (Baseline \times Growth\ Rate) + (\#EV \times EV\ Consumption)$$

5.1.2 Section 2: Economic considerations

This section of the model evaluates the cost associated with a certain energy mix. For this reason, the cost of each technology was collected. Most of the values are presented in ranges since it is possible for them to vary, especially in fossil fuel generation due to their high dependence on fuel prices. All costs are shown per unit of energy generated (see Table 5.5) and were extracted from discussions with industry experts.

Some simplifications were made in the analysis. Cost ranges were simplified by considering the mean value (see Table 5.5). Since these values originated from the European energy market, capital costs are considered sunk costs and, therefore, they are not represented in the cost breakdown (see Table 5.5). The costs represented in the breakdown are fuel price and transportation, and CO_2 allowances for emitters, and Operations & Maintenance (O&M) for all technologies. Technologies involving natural gas consider prices of shipping and regasification. Lastly, the cost for the submarine connection was extracted from the specifications of the original project, 400MW and 375M€, which included both substations (Valencia and Mallorca) and the submarine cable net (Red Eléctrica de España, 2012).

Technology	Cost Range (€/MWh)	Simplified Cost (€/MWh)	Cost Breakdown
Coal	20-70	45	Fuel price + CO_2 allowances + transportation + O&M
NG turbines	50-55	52.5	Fuel price + CO_2 allowances + transportation(ship) & regasification + O&M
Cogeneration	0-20	10	CO_2 allowances + transportation + O&M
Onshore wind	0-5	2.5	O&M
Concentrating solar thermal	0-5	2.5	O&M
Concentrating solar PV	0-5	2.5	O&M
Microwind	0-5	2.5	O&M
Diesel	80-100	90	Fuel price + CO_2 allowances + transportation + O&M
Combined cycle	50-55	52.5	Fuel price + CO_2 allowances + transportation + O&M
Waste	0-20	10	CO_2 allowances + transportation + O&M
Utility-scale solar PV	0-5	2.5	O&M
Hybrid PV/thermal	0-5	2.5	O&M
Distributed solar PV	0-5	2.5	O&M
Biomass	0-20	10	CO_2 allowances + transportation + O&M
Submarine connection	107	107	Set-up

Table 5.5: Technology cost characterization. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from industry experts and Project Rómulo, interconexión eléctrica Peninsula-Baleares (Red Eléctrica de España, 2012)

Once the cost per unit of energy is determined for each technology, the cost for different energy mixes can be modeled by using the following equation.

$$\text{Total Cost } (€) = 24 \times 365 \times \sum_{i=1}^{15} (\#\text{unit}_i \times \text{CF}_i \times \text{UPC}_i \times \text{Cost}_i)$$

Where:

$\#unit_i$ is the number of units of a certain technology

CF_i is the related capacity factor

UPC_i is the capacity of each unit

$Cost_i$ is the cost per unit of energy for each technology

5.1.3 Section 3: Environmental considerations

In this section, the environmental impact of each potential energy mix is modeled. Environmental impact is represented in the form of pollution-oriented indicators in terms of greenhouse gas (GHG) emissions, freshwater eutrophication, particulate matter formation, and aquatic ecotoxicity; but also, land-use indicators as a measure for impact on biodiversity. GHG emissions are quantified in "kg CO_2 eq." and consider carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs) emissions representing global warming potential (GWP). Freshwater eutrophication values are measured in "g P eq." and represent the augmentation of nutrients level in freshwater bodies, potential cause for the extreme growth of aquatic plants and algae blooming. Particulate matter is measured in "kg PM10 eq." and include emissions of fine particles (<10 μm) and particulates originated from SO_2, NO_x, sulfate, and ammonia emissions. The exposure to these particles has the highest human health impact (Ezzati, M. et al, 2004). Freshwater ecotoxicity represents a roundup of toxic substances for aquatic life and it is measured in "kg1,4-DB 4 eq.". Lastly, habitat change strongly contributes to biodiversity loss. Since land use can be a potential cause of habitat change, it can also be used as an indicator of biodiversity impact. Land use is measured in "m^2 a" and represents the area occupied by each technology during their life cycle (Hertwich, E.G. et al, 2015).

A widely accepted Life Cycle Assessment (LCA) method, ReCiPe version 1.08 (Goedkoop, M. et al 2008), is used to determine these values (see Figure 5.4). They were calculated from the resulting emissions throughout the life cycle of each technology and presented as impact unit per unit of energy (see Figure 5.4). Life cycle analysis includes building materials, construction, equipment manufacturing, generators, transportation, grid connection infrastructure, and decommissioning. For those technologies involving fossil fuels, LCA also considers fuel extraction and transport to the power plant (Hertwich, E.G. et al, 2015).

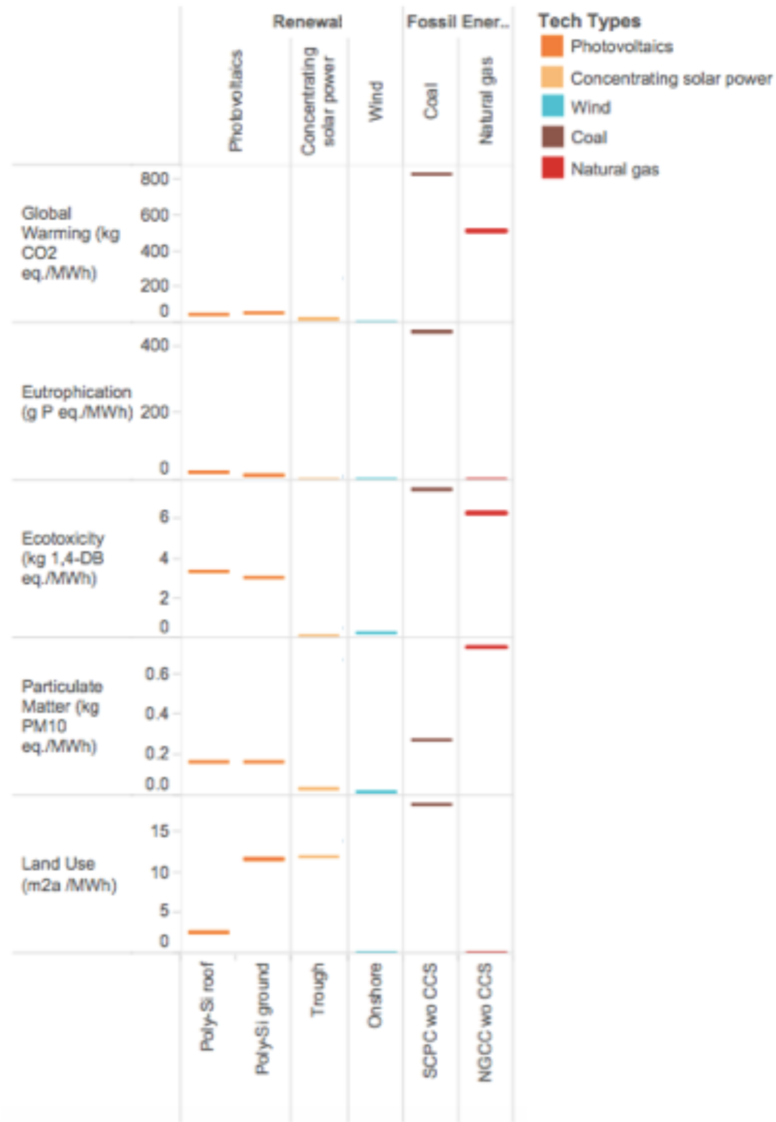

Figure 5.4: Environmental Impact Assessment per technology. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies (Hertwich, E.G. et al 2015)

Since the referenced paper provides a wide range of technologies and regions, information had to be parsed. In relation to the region, OECD Europe was selected for obvious reasons. In terms of the technologies, the selection considered the current technologies used in the Balearic Island or Spain. Thus, in the case of coal generation, supercritical pulverized coal (SCPC) without carbon capture and storage (CCS) was used (Patierno, M. et al, 2017.). For natural gas, natural gas combined cycle without CCS was assumed. Polycrystalline silicon (Poly-Si) panels in both ground (utility-scale solar) and roof (distributed solar) installations were selected because they are currently the most widely used. Through technology for concentrating solar power. Lastly, onshore wind was selected as offshore wind was dismissed for the reasons discussed in previous chapters. In addition, some simplifications have been made since the referred analysis does not consider certain technologies involved in this study. Both concentrating solar PV and thermal are considered as concentrating solar. In addition, Hybrid PV/thermal is assigned the concentrating solar values as an estimation. Both NG turbines and combined cycle use the values from NGCC without CCS. Cogeneration is considered to have values around 50% of NGCC. Microwind is considered equivalent to onshore wind. Diesel values are considered to be like coal values and assume environmental implications of diesel generation could be as bad as coal in the worst-case scenario. Since biomass and waste are considered together in the assessment (Hertwich, E.G. et al, 2015) and because biomass is considered 50% renewable under Spanish documentation (REE, 2016), they are also considered as being 50% of NGCC values. Lastly, the submarine connection is considered to have no environmental impacts of any type related to its electricity generation since it does not generate electricity per se (see Table 5.6).

	Impact				
Technology	*GW* (kg CO_2 eq./MWh)	*EU* (g P eq./MWh)	*EC* (kg1,4-DB4eq. /MWh)	*PM* (kg PM 10eq/MWh)	*LU* (m^2 a/MWh)
Utility-scale solar PV	58.485	20.575	3.055	0.174	11.791
Distributed solar PV	56.369	27.455	3.380	0.172	2.673
Concentrating solar thermal	23.279	4.761	0.134	0.040	12.067
Onshore wind	8.371	5.864	0.297	0.027	0.261
Coal	838.785	444.007	7.535	0.276	18.508
NG turbines	515.948	4.540	6.326	0.738	0.163
Combined Cycle	515.948	4.540	6.326	0.738	0.163
Cogeneration	257.974	2.270	3.163	0.369	0.082
Hybrid PV/thermal	23.279	4.761	0.134	0.040	12.067
Concentrating solar PV	23.279	4.761	0.134	0.040	12.067
Microwind	8.371	5.864	0.297	0.027	0.261
Diesel	838.785	444.007	7.535	0.276	18.508
Waste	257.974	2.270	3.163	0.369	0.082
Biomass	257.974	2.270	3.163	0.369	0.082
Submarine connection	0.000	0.000	0.000	0.000	0.000

Table 5.6: Environmental Impact Assessment per technology. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies (Hertwich, E.G. et al 2015)

Once the different types of impacts per unit of energy are determined for each technology, the total impact (for each type of impact) for different energy mixes can be modeled by using the following equations.

$$\text{Total GW potential } (\text{kg CO2 eq.}) = 24 \times 365 \times \sum_{i=1}^{15} (\#\text{unit}_i \times \text{CF}_i \times \text{UPC}_i \times \text{GW}_i)$$

$$\text{Total EU potential } (\text{g P eq.}) = 24 \times 365 \times \sum_{i=1}^{15} (\#\text{unit}_i \times \text{CF}_i \times \text{UPC}_i \times \text{EU}_i)$$

$$\text{Total EC potential } (\text{kg1,4} - \text{DB4eq.}) = 24 \times 365 \times \sum_{i=1}^{15} (\#\text{unit}_i \times \text{CF}_i \times \text{UPC}_i \times \text{EC}_i)$$

$$\text{Total PM potential } (\text{kgPM10eq}) = 24 \times 365 \times \sum_{i=1}^{15} (\#\text{unit}_i \times \text{CF}_i \times \text{UPC}_i \times \text{PM}_i)$$

$$\text{Total Land Use } (m^2\ \text{a}) = 24 \times 365 \times \sum_{i=1}^{15} (\#\text{unit}_i \times \text{CF}_i \times \text{UPC}_i \times \text{LU}_i)$$

Where:

$\#unit_i$ is the number of units of a certain technology

CF_i is the related capacity factor

UPC_i is the capacity of each unit

GW_i is the global warming potential per unit of energy for each technology

EU_i is the eutrophication per unit of energy for each technology

EC_i is the ecotoxicity per unit of energy for each technology

PM_i is the particulate matter per unit of energy for each technology

LU_i is the land use per unit of energy for each technology

5.2 Scenarios

Once the common parameters for all scenarios are established and the model is set up, the different scenarios need to be defined. Each year, changes in demand will be matched by increasing and decreasing the number of units of each technology according to the scenario in place. At the end of the simulations, results from the economic and the environmental sections will be collected.

The methodology used in the calculations considers the following steps: (1) identify the constant contributions, (2) determine the evolution of the demand, (3) define the technologies increasing and decreasing generation, (4) through calculations and iteration, establish the number of units per technology each year, and finally, (5) input this data in Insight Maker to run the model.

In all cases, a simplification was made. Although 22.19% of the demand is currently covered by auxiliary generation (oil and natural gas), due to the need to eliminate this technology, lack of data, technology similarities and in order to promote a reliable energy mix, all that generation will be considered as NGCC at the beginning of the simulation (in 2020).

5.2.1 Scenario 1: Natural gas focus

Under this scenario, natural gas is proposed as the major source of electricity in the Balearic Islands by the end of 2030 (see Figure 5.5). The submarine connection, waste, cogeneration, natural gas turbines, and renewable generation contributions stay constant. No other types of generation are introduced. Current diesel and coal generation are replaced progressively by NGCC throughout the 10-year period, and the rise in demand is covered by this technology (see Table C.1). As a result, generation in this archipelago will be almost entirely from natural gas.

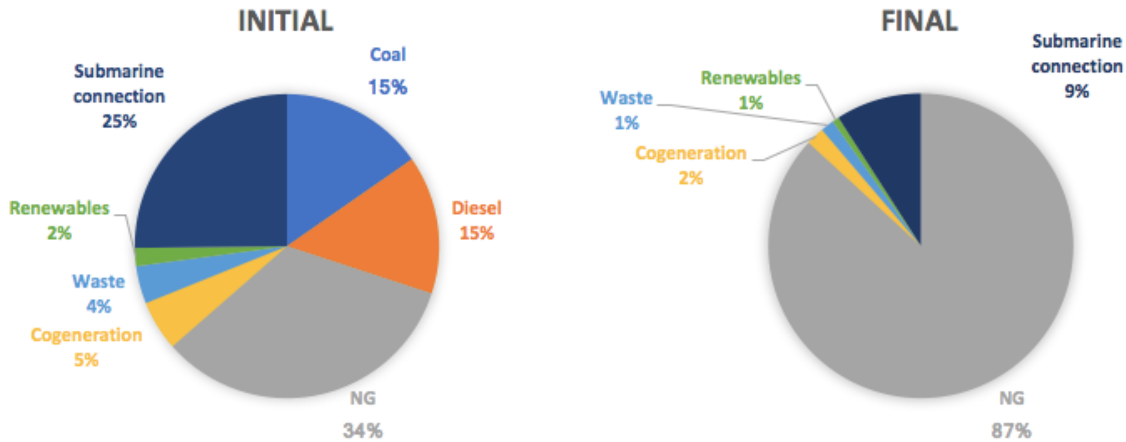

Figure 5.5: Generation contribution data for Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

Note generation inputs are measured in units (see Table 5.7) and need to be multiplied by the corresponding unit power capacity and capacity factor in order to determine the actual energy generated (see Section 5.1.1.1).

	Initial contribution		Final contribution	
Technology	*#unit*	*Capacity (GW)*	*#unit*	*Capacity (GW)*
Coal	11	0.33	0	0
Diesel	57	0.57	0	0
NG turbines	7	0.21	7	0.21
Combined Cycle	141	1.41	1,169	11.69
Cogeneration	24	0.72	24	0.72
Waste	12	0.12	12	0.12
Onshore wind	3	0.003	3	0.003
Utility-scale solar PV	116	0.116	116	0.116
Submarine connection	3	0.3	3	0.3

Table 5.7: Generation contribution data for Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

5.2.2 Scenario 2: Submarine connection expansion

The goal of this scenario is to evaluate an expansion of the energy supplied by the connection with the peninsula to provide nearly 100% of the required energy of the islands (see Figure 5.6). This expansion would take place in 2 phases (2025 and 2030) due to the complexity of these projects. Although conventional power plants will cover the annual demand increase due to their current extra capacity while these phases are being completed, they would be the first to be replaced (see Table C.2). Natural gas turbines, cogeneration, waste, and renewable generation remain constant. No new resources are introduced. By the end of the 10-year period, most of the energy mix would be supplied by the submarine connection with the peninsula (see Table 5.8).

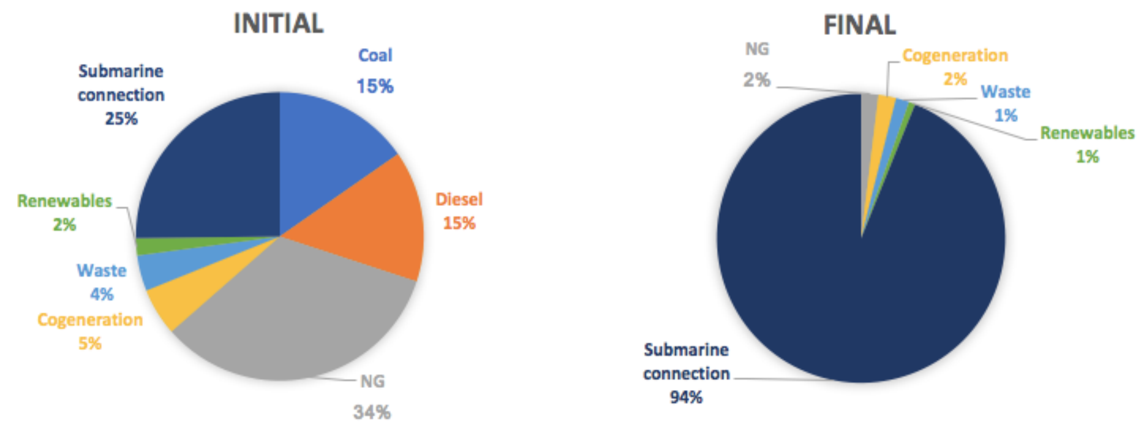

Figure 5.6: Generation contribution data for Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

	Initial contribution		Final contribution	
Technology	*#unit*	*Capacity (GW)*	*#unit*	*Capacity (GW)*
Coal	11	0.33	0	0
Diesel	57	0.57	0	0
NG turbines	7	0.21	7	0.21
Combined Cycle	141	1.41	0	0
Cogeneration	24	0.72	24	0.72
Waste	12	0.12	12	0.12
Onshore wind	3	0.003	3	0.003
Utility-scale solar PV	116	0.116	116	0.116
Submarine connection	3	0.3	30	3

Table 5.8: Generation contribution data for Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

5.2.3 Scenario 3: 50% natural gas, 50% renewable sources

This scenario provides for the coexistence of conventional and new renewable resources in an approximately 50% proportion of natural gas and 50% renewables (see Figure 5.7). Because of the nature of the current energy mix, the changes allow keeping natural gas in the same proportion and developing new renewable infrastructure. New renewable resources are introduced. The submarine connection, cogeneration, waste, and NG turbines contribution are fixed. Lastly, existing coal and diesel generation and the increase in demand are progressively covered by NG and renewables in the same proportion (see Table C.3). Thus, in the final situation, coal and diesel are eliminated and demand is supplied mainly by natural gas, renewables, and the submarine connection (see Table 5.9).

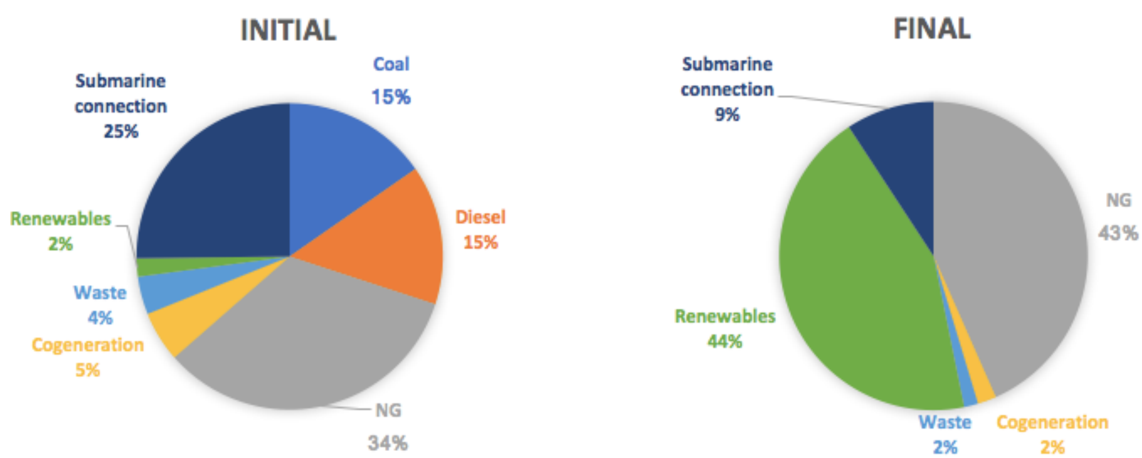

Figure 5.7: Generation contribution data for Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

	Initial contribution		Final contribution	
Technology	*#unit*	*Capacity (GW)*	*#unit*	*Capacity (GW)*
Coal	11	0.33	0	0
Diesel	57	0.57	0	0
NG turbines	7	0.21	7	0.21
Combined Cycle	141	1.41	561	5.61
Cogeneration	24	0.72	24	0.72
Waste	12	0.12	12	0.12
Onshore wind	3	0.003	701	0.701
Utility-scale solar PV	116	0.116	1,070	1.07
Submarine connection	3	0.3	3	0.3
Biomass	0	0	5	0.01
Microwind	0	0	233,757	0.701
Distributed Solar PV	0	0	535,181	1.07
Hybrid PV/thermal	0	0	152,909	1.07
Concentrating solar PV	0	0	42,815	1.07
Concentrating solar thermal	0	0	163	0.815

Table 5.9: Generation contribution data for Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

5.2.4 Scenario 4: 20% renewables, 40% natural gas, 40% submarine connection

From the previous findings, it is appropriate to test a combined approach. Renewable generation requires large amounts of land which are especially limited in an island, so its share is decreased to 20% of the final demand. Submarine connection expansions are capital intensive increasing the cost, therefore a lower proportion of 40% may yield better results. Finally, natural gas is considered a very flexible and reliable source with less environmental impact than diesel and coal, becoming the optimum option for the remaining 40% (see Figure 5.8). Thus, new renewable resources are added to the mix and contribute in the same proportion to the assigned 20% while cogeneration, waste, and NG turbines contributions remain fixed. Coal and diesel generations is replaced progressively; their share and the increase in demand are covered by NG, renewables, and the submarine connection (see Table 5.10).

In terms of the calculations, renewables and combined cycle generation will cover the remaining demand after fixed contributions for the first 4 years. In the 5th year, an expansion of the submarine connection will be added to the mix. From that point on, renewables and combined cycle will complement the submarine connection until they reach the final percentages (see Table C.4). Note part of the renewable infrastructure developed in the first 4 years may be affected by the extension of the submarine connection, but it would be back in use shortly after because of the progressive increase in demand (see Table C.4).

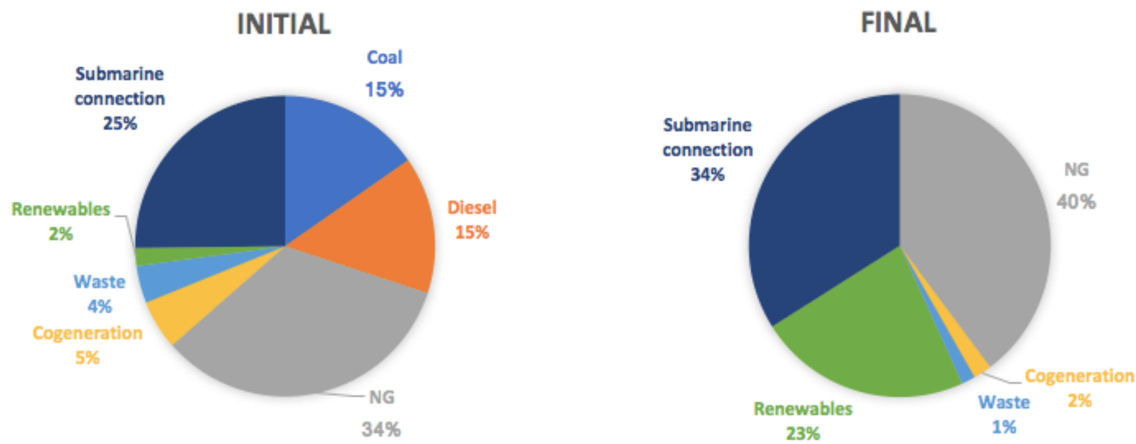

Figure 5.8: Generation contribution data for Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

	Initial contribution		Final contribution	
Technology	*#unit*	*Capacity (GW)*	*#unit*	*Capacity (GW)*
Coal	11	0.33	0	0
Diesel	57	0.57	0	0
NG turbines	7	0.21	7	0.21
Combined Cycle	141	1.41	513	5.13
Cogeneration	24	0.72	24	0.72
Waste	12	0.12	12	0.12
Onshore wind	3	0.003	364	0.364
Utility-scale solar PV	116	0.116	555	0.555
Submarine connection	3	0.3	11	1.1
Biomass	0	0	5	0.01
Microwind	0	0	121,305	0.364
Distributed Solar PV	0	0	277,725	0.555
Hybrid PV/thermal	0	0	79,350	0.555
Concentrating solar PV	0	0	22,218	0.555
Concentrating solar thermal	0	0	84	0.42

Table 5.10: Generation contribution data for Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

Chapter 6. Results

In the following pages, the results obtained from Insight Maker are presented. Each scenario is compared with the original energy mix (current situation) through absolute values represented on graphs, and also by the analysis per unit of energy produced. At the end of the chapter, the final results of every scenario will be compared with the rest of the considered scenarios.

6.1 Scenario 1: Natural gas focus

Applying the methodology already introduced, it should be noted that the changes made in technologies used in the generation do not affect supply. Generation matches demand at all times (see Figure 6.1). As more electricity is generated, the cost increases (see Figure 6.2). Following the same trend, environmental factors, such as ecotoxicity, particulate matter, and global warming also increase in time (see Figures 6.3, 6.4, and 6.5). However, other environmental aspects like eutrophication and land use decrease rapidly when eliminating coal and diesel generation and increasing the use of NGCC (see Figures 6.6 and 6.7).

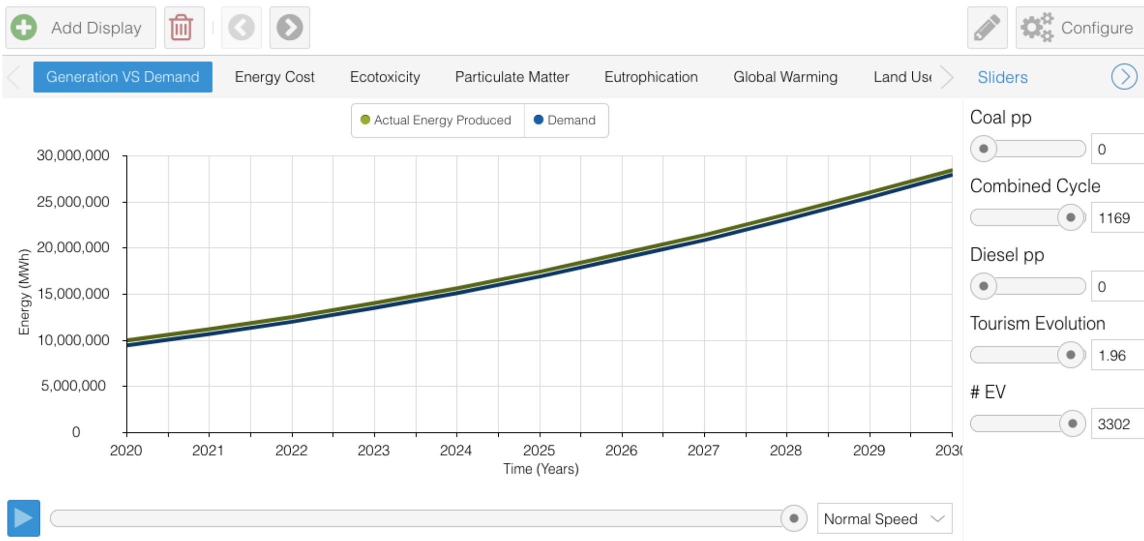

Figure 6.1: Energy produced vs demand, Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

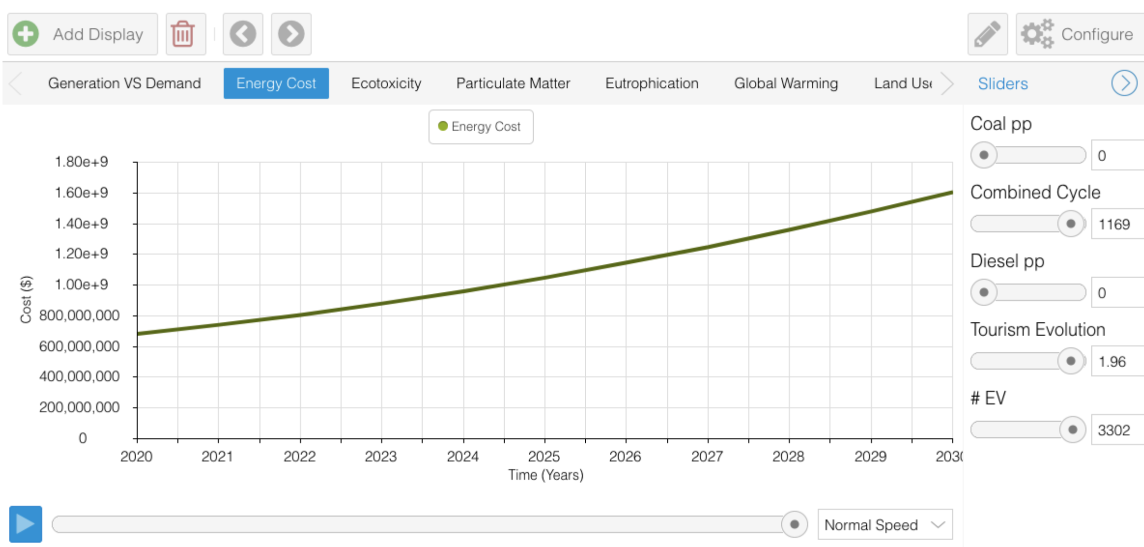

Figure 6.2: Energy cost, Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

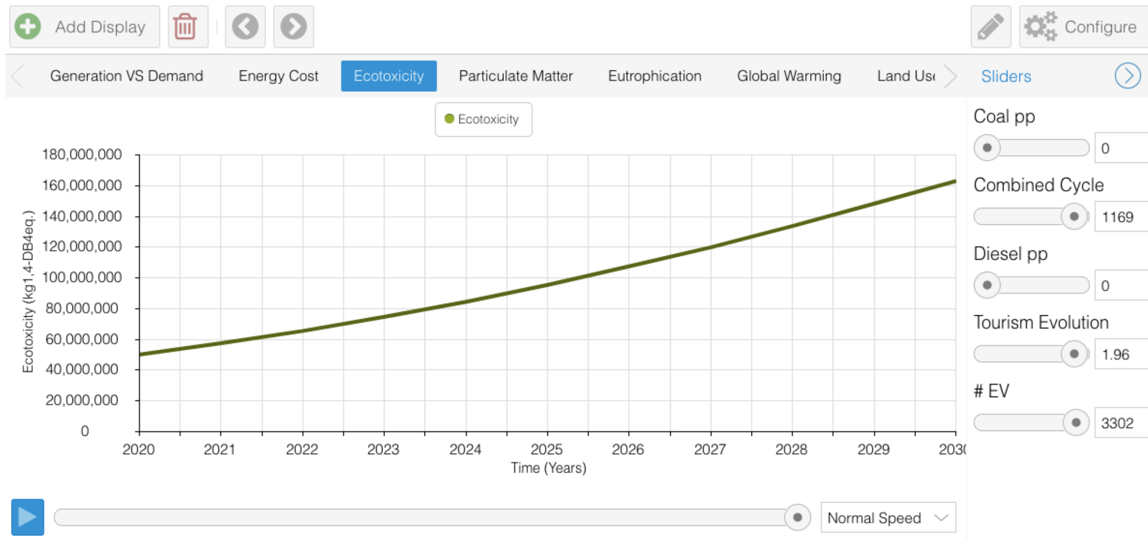

Figure 6.3: Ecotoxicity, Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

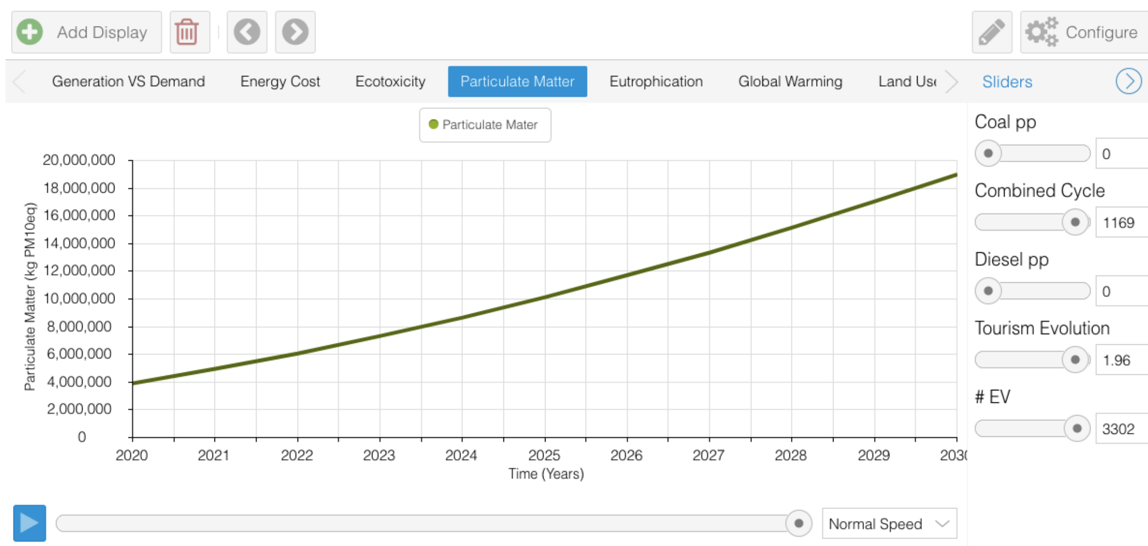

Figure 6.4: Particulate matter, Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

Figure 6.5: Global warming, Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

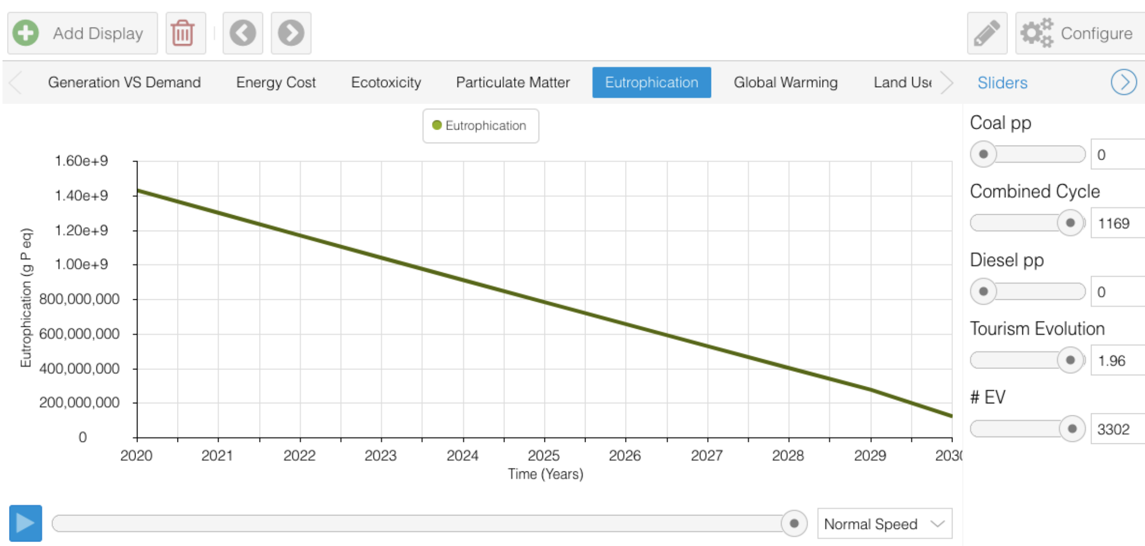

Figure 6.6: Eutrophication, Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

Figure 6.7: Land use, Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

If normalized per MWh generated, new insights are created from the results obtained with Insight Maker. Most of the factors are higher in the initial energy mix, especially for eutrophication. In the case of ecotoxicity and particulate matter, final values are slightly higher than initial values but are low in either case (see Figure 6.8). Note that the ordinate axis refers to the collection of units per MWh.

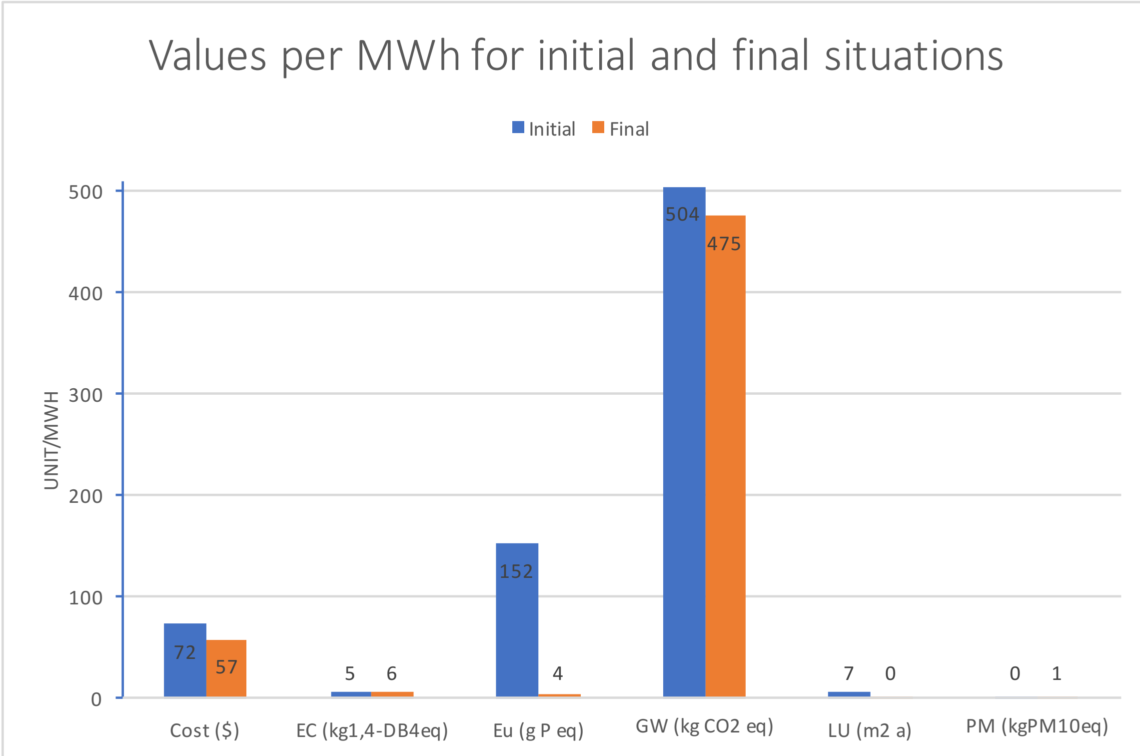

Figure 6.8: Values per MWh comparison for initial and final situations, Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from sources mentioned in text

6.2 Scenario 2: Submarine connection expansion

Balancing generation and demand matched even with the aggressive introduction of the expansion of the submarine connection in two phases (see Figure 6.9), it is clear that this strategy has a significant impact on the economics and the environmental factors associated with electricity generation. The cost of the energy mix increases with time as generation increases in sharp increments when the expansions are introduced (see Figure 6.10). In the case of environmental factors, extreme falls occur as expected given that the submarine connection does not contribute to environmental impacts in terms of electricity generation (see Figure 6.11, 6.12, 6.13, 6.14, and 6.15). However, there are environmental impacts but they take place on the mainland where generation occurs. This is not factored into this analysis.

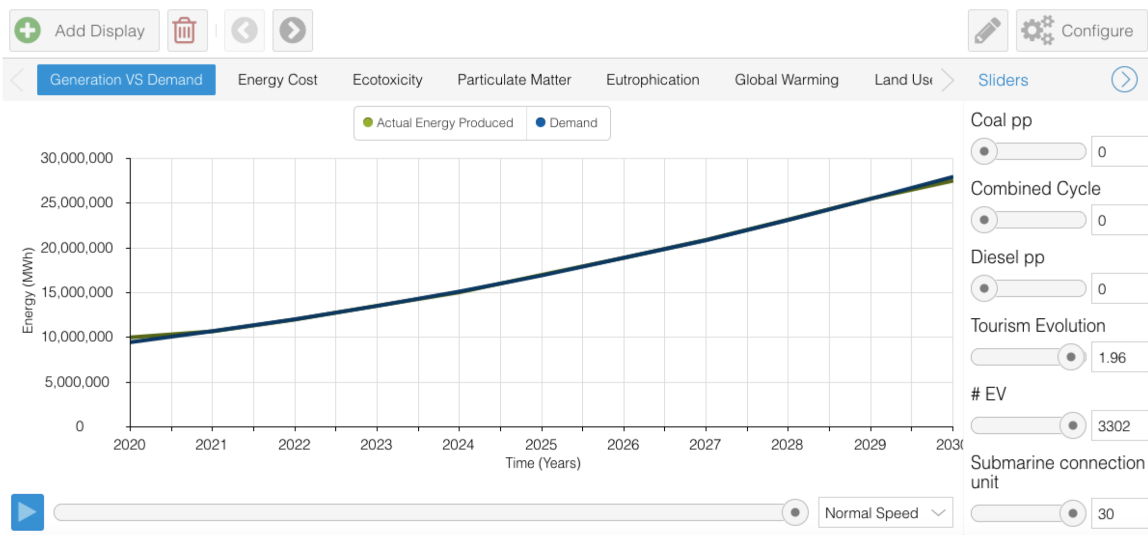

Figure 6.9: Energy produced vs demand, Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

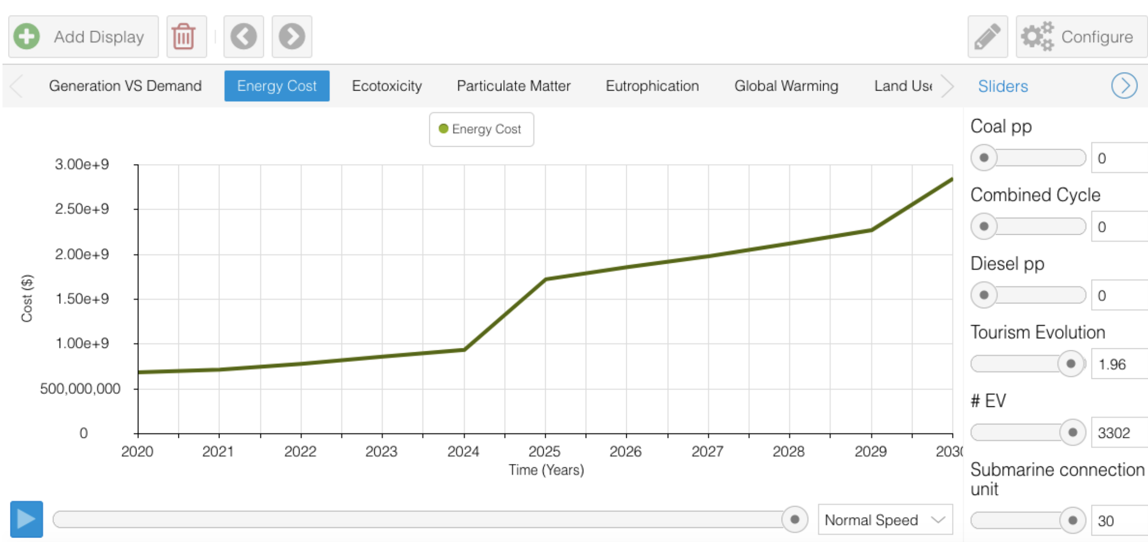

Figure 6.10: Energy cost, Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

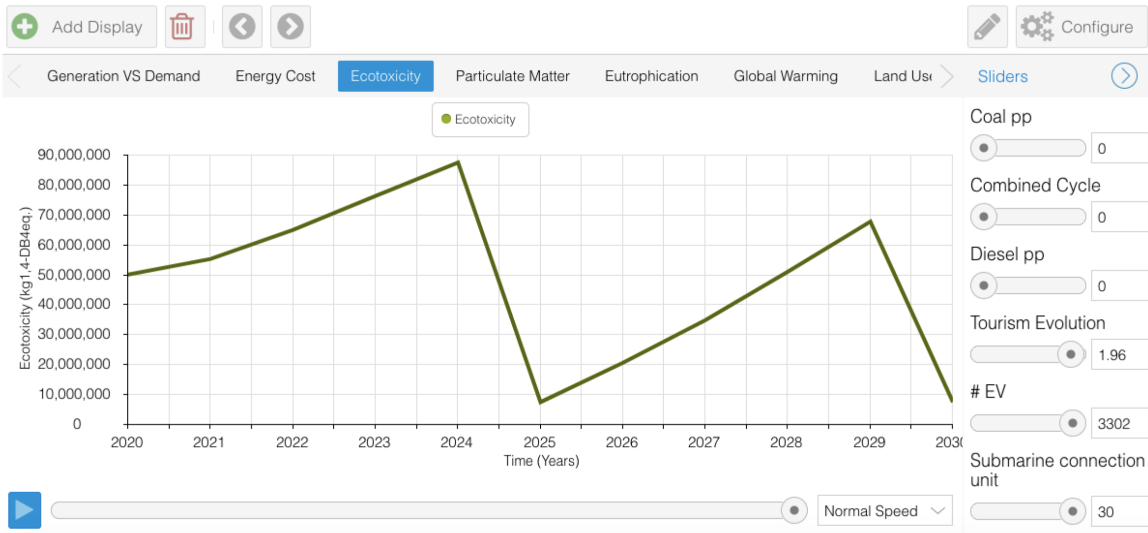

Figure 6.11: Ecotoxicity, Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

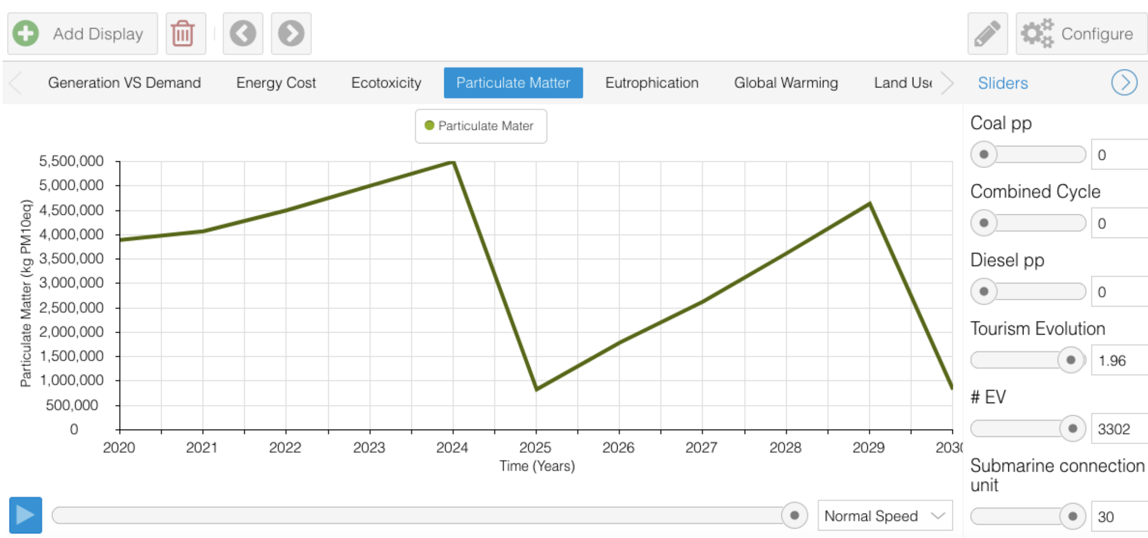

Figure 6.12: Particulate matter, Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

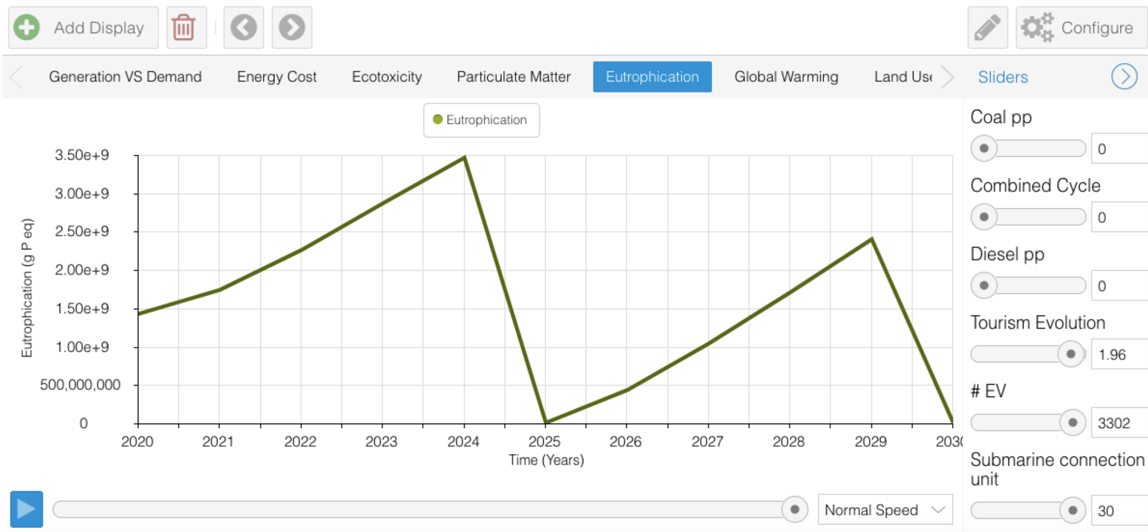

Figure 6.13: Eutrophication, Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

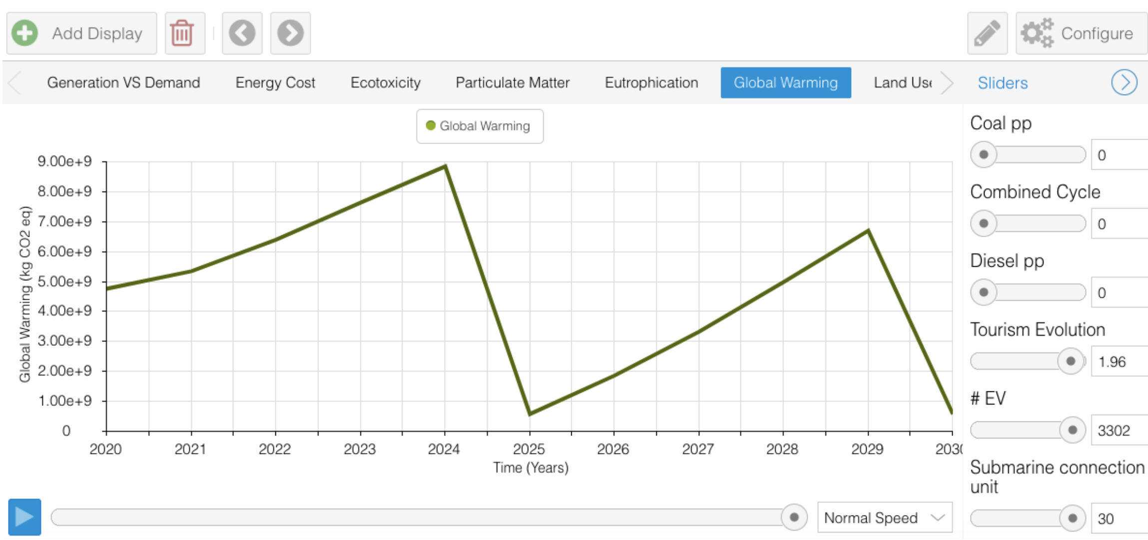

Figure 6.14: Global warming, Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

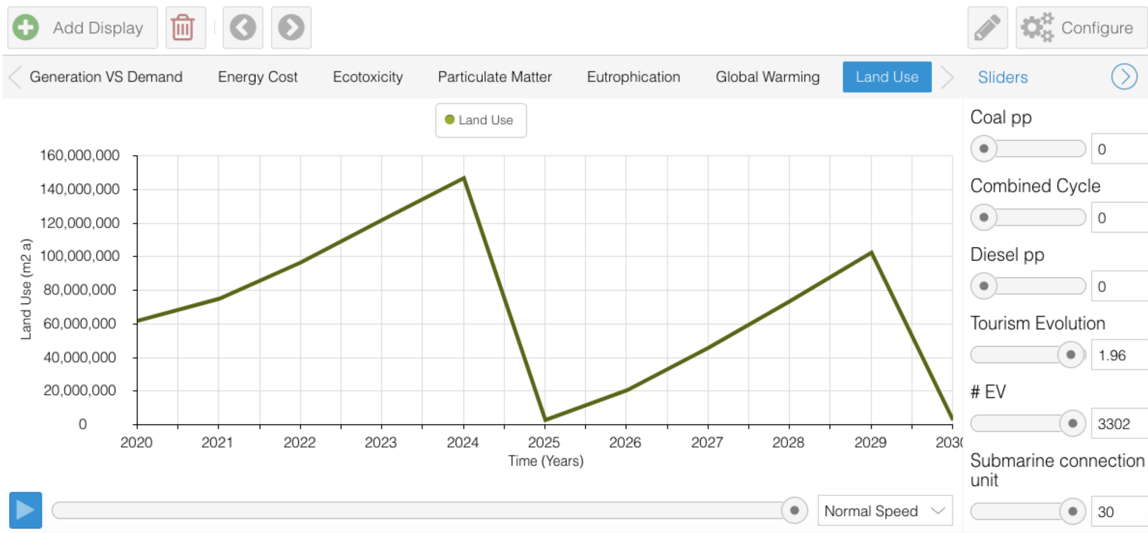

Figure 6.15: Land use, Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

Regarding relative values per MWh for the initial and final energy mixes, in this case, the results coincide with the trends reflected in the graphs. In terms of costs, an expansion of the submarine connection appears to be significantly more capital intensive. In contrast, environmental impact is much lower for any of the considered factors (see Figure 6.16) but this is only because the environmental impacts have been displaced to the mainland. Note the ordinate axis refers to the collection of units per MWh.

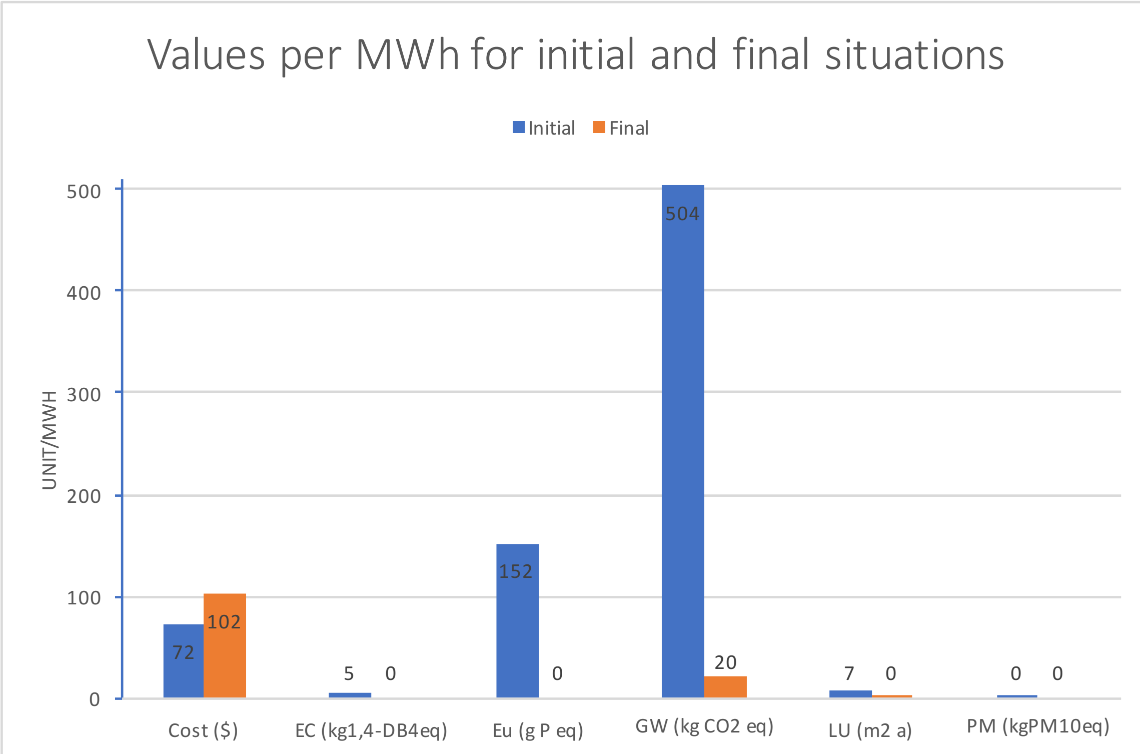

Figure 6.16: Values per MWh comparison for initial and final situations, Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from sources mentioned in text

6.3 Scenario 3: 50% natural gas, 50% renewable sources

Once generation and demand are properly matched (see Figure 6.17), clear trends for the considered factors were evident from Insight Maker. After an aggressive introduction of renewables in the market, costs decrease sharply. This fall is compensated and surpassed by a progressive increase due to the rise in demand, and therefore, generation (see Figure 6.18). The same trend is shown for several environmental impact factors: ecotoxicity, particulate matter, and global warming (see Figures 6.19, 6.20, and 6.21). Eutrophication experiences a clear fall when replacing coal and diesel with other technologies (see Figure 6.22). Finally, land use shows an increase correlated with the level of introduction of renewable technologies as expected for their land intensive characteristics (see Figure 6.23).

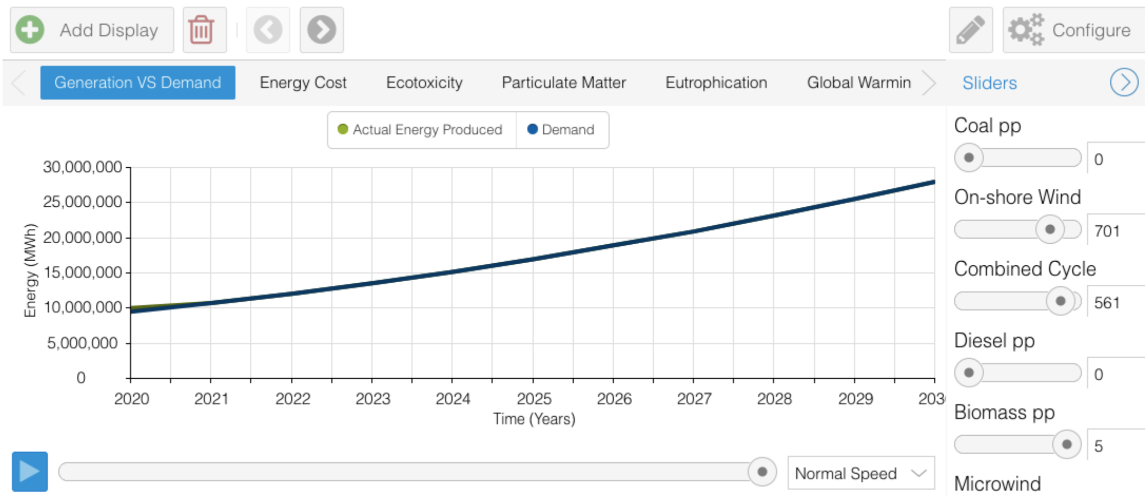

Figure 6.17: Energy produced vs demand, Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

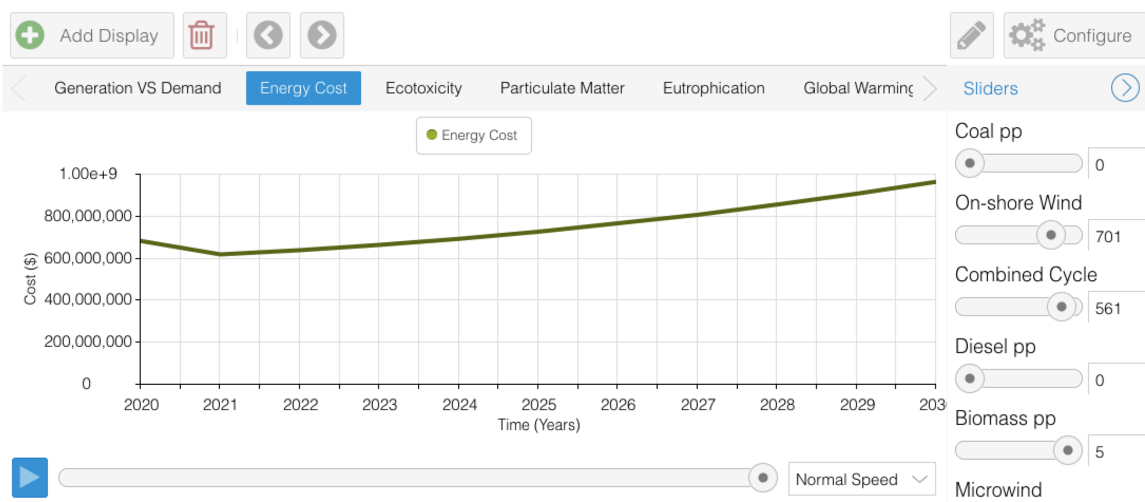

Figure 6.18: Energy cost, Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

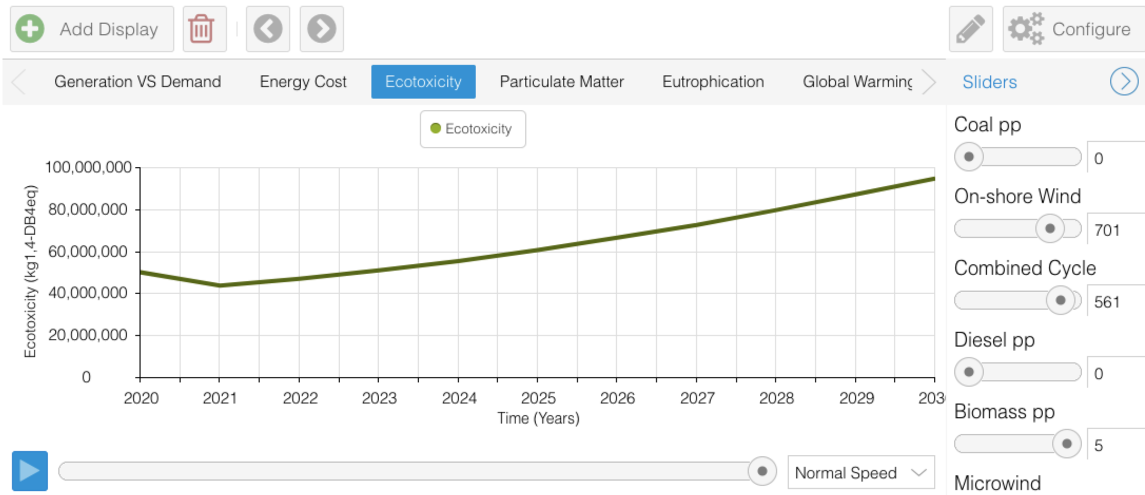

Figure 6.19: Ecotoxicity, Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

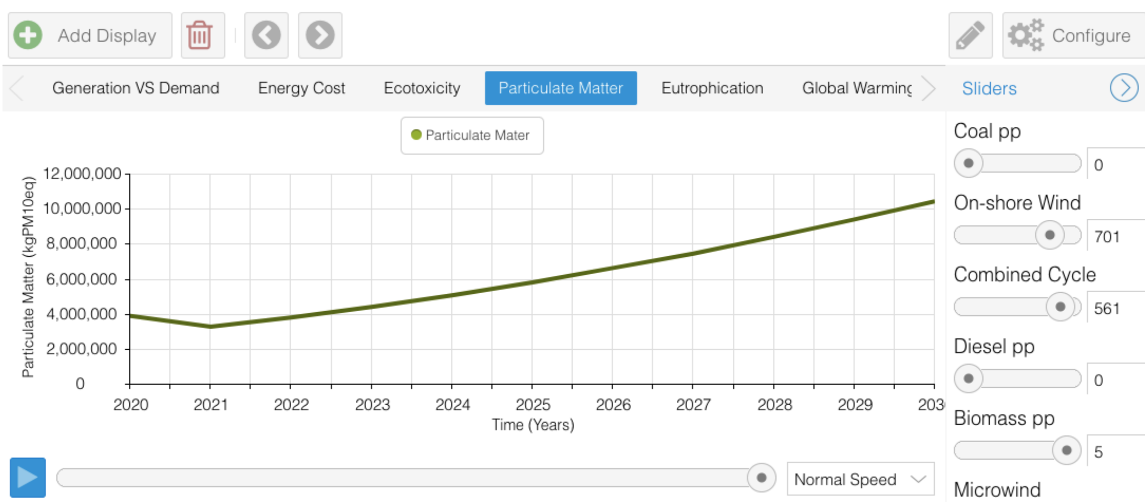

Figure 6.20: Particulate Matter, Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

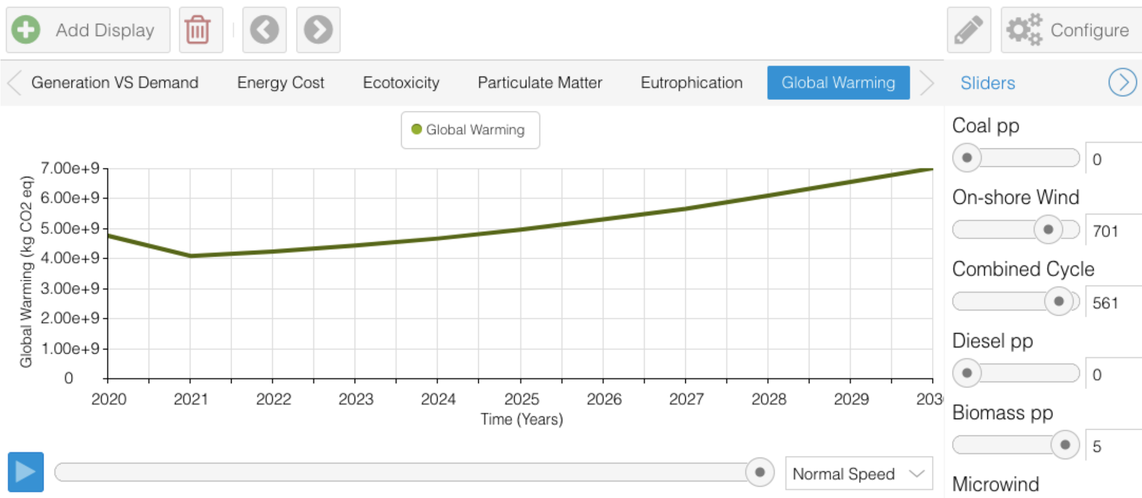

Figure 6.21: Global warming, Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

Figure 6.22: Eutrophication, Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

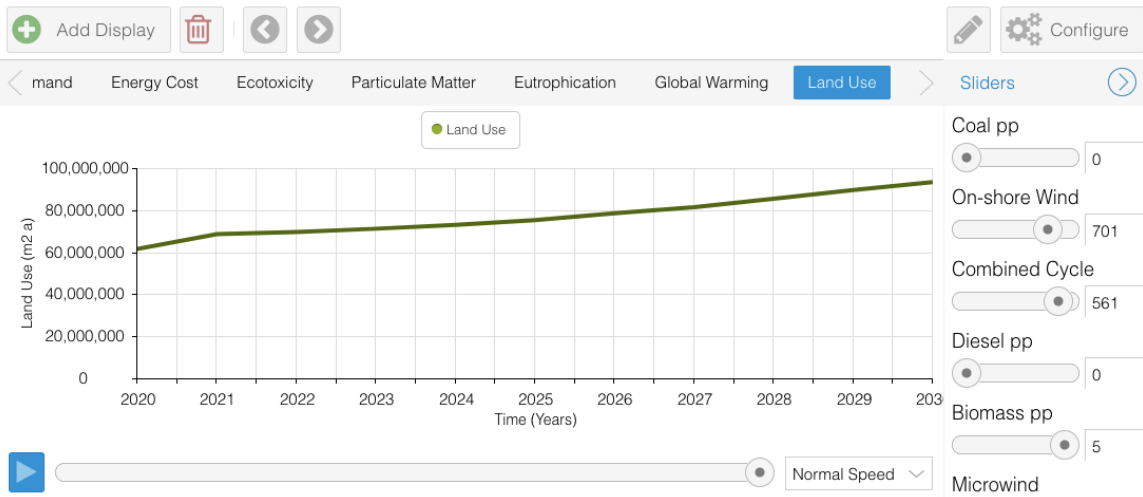

Figure 6.23: Land use, Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

When normalized per MWh, it can be seen that the final scenario has better results for all the parameters (see Figure 6.24). In terms of cost, ecotoxicity, global warming, and land use, the reduction is approximately 50%, while the reduction in eutrophication is even larger (~5% of the original value). Particulate matter emissions are very low in both cases. Note the ordinate axis refers to the collection of units per MWh.

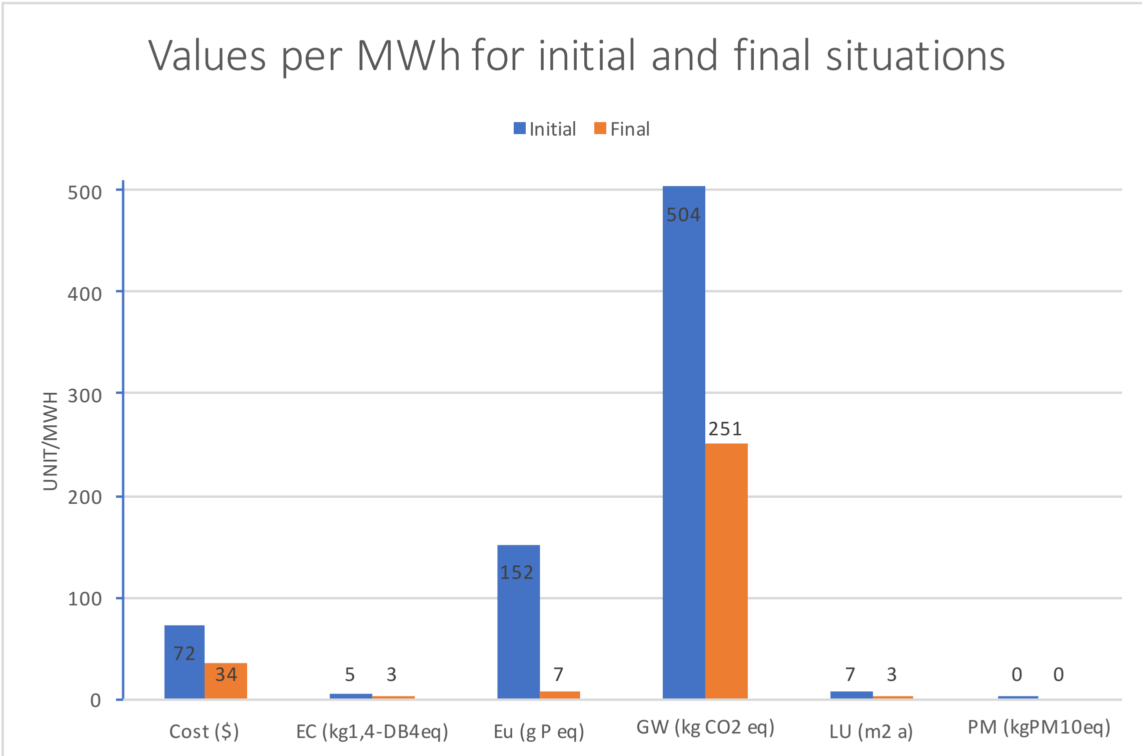

Figure 6.24: Values per MWh comparison for initial and final situations, Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from sources mentioned in text

6.4 Scenario 4: 20% renewable, 40% natural gas, 40% submarine connection

Following the complex process of matching demand and generation when a large variety of technologies are involved (see Figure 6.25), economic and environmental results can be analyzed. Energy costs reflect a progressive rise aligned with the increase in generation and experience a sharp increment when the expansion in the submarine connection is implemented (see Figure 6.26). As in the previous scenario, the environmental factors ecotoxicity, particulate matter, and global warming follow the same trend with a slight decline at the beginning when more renewables are introduced and a significant fall due to the extension in the submarine connection. However, most of the time these values increase according to the rise in generation (see Figures 6.27, 6.28, and 6.29). As in scenario 1 and 3, eutrophication values drastically drop as a result of eliminating coal and diesel generation (see Figure 6.30). Finally, in the case of land use, a more diverse energy mix helps to offset the increase in land use from new generation to supply the extra demand. The trend reflects slight increases due to renewable penetration and additional generation and decreases perceptibly when the submarine connection is expanded (see Figure 6.31).

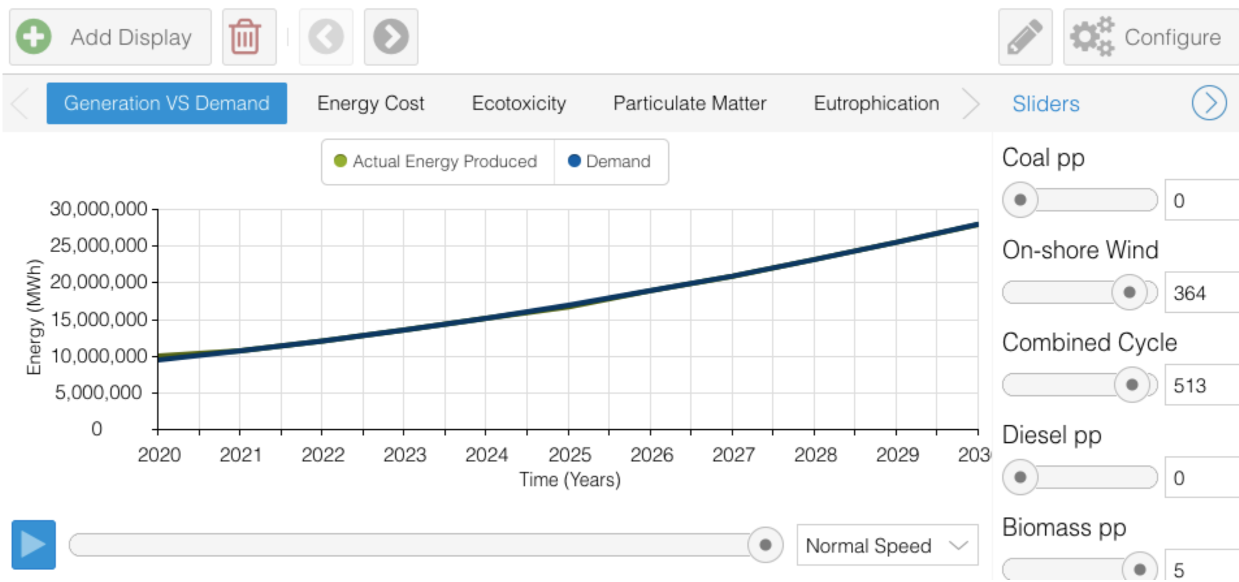

Figure 6.25: Energy produced vs demand, Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

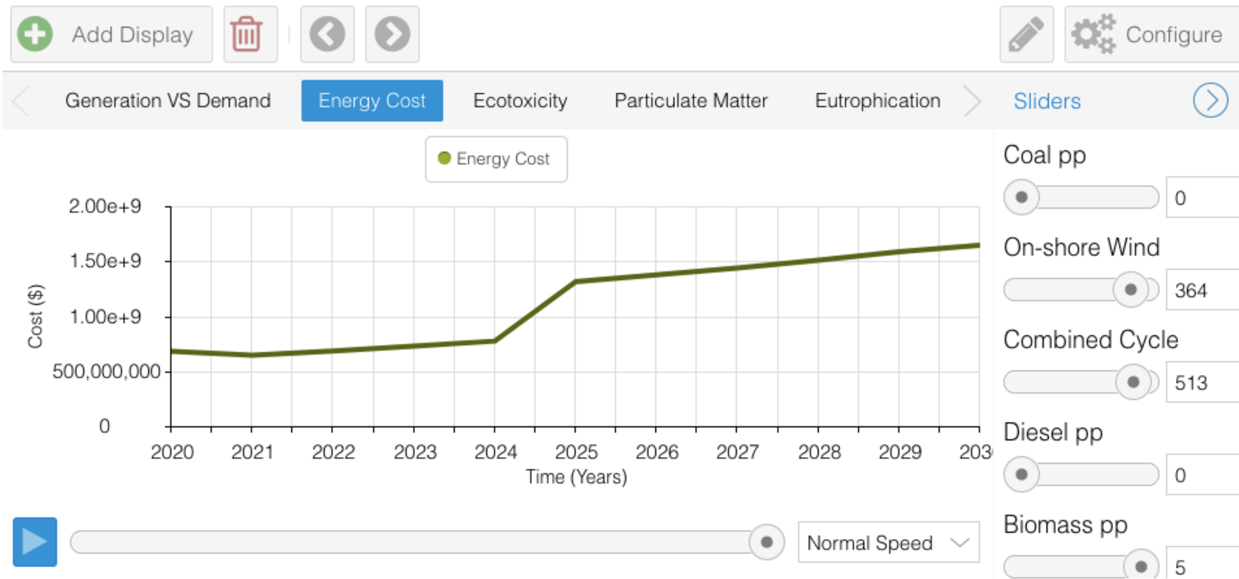

Figure 6.26: Cost, Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

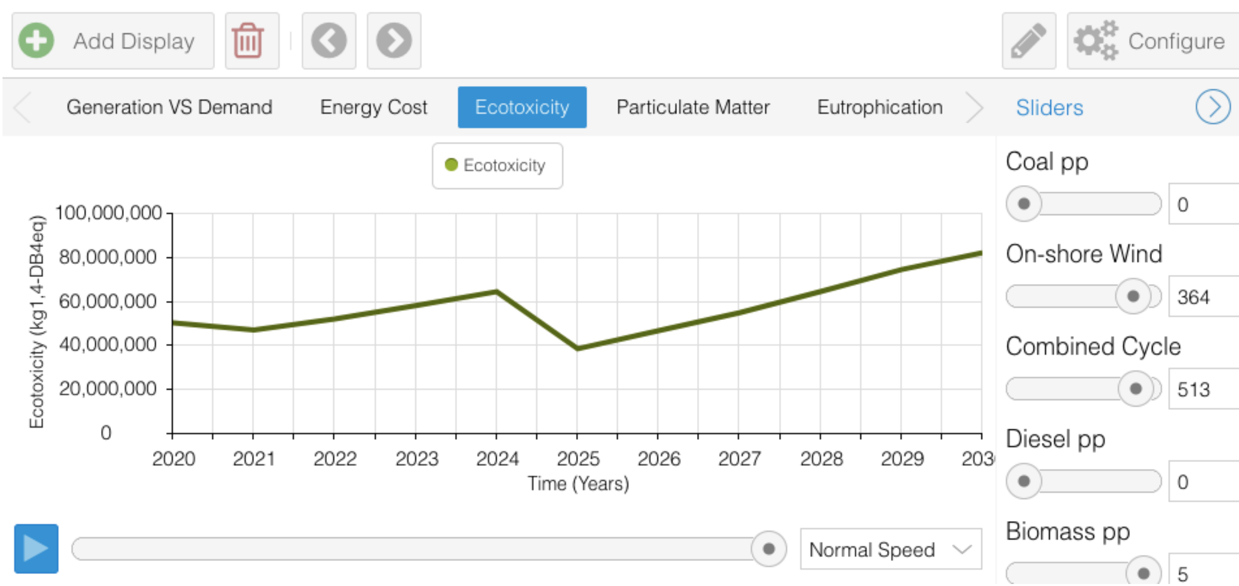

Figure 6.27: Ecotoxicity, Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

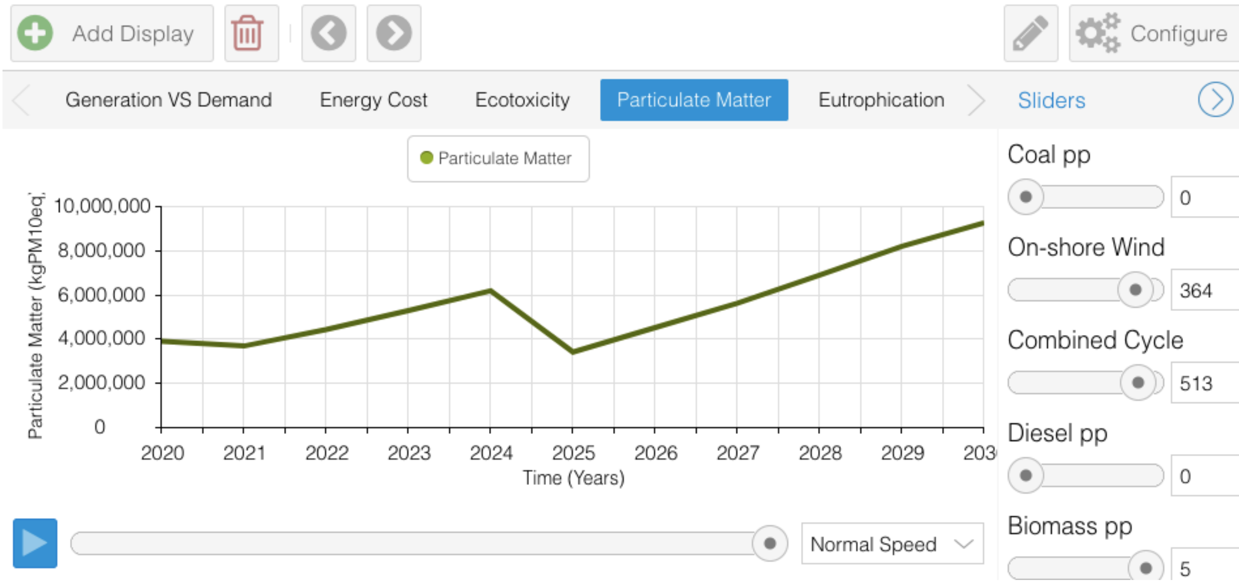

Figure 6.28: Particulate Matter, Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

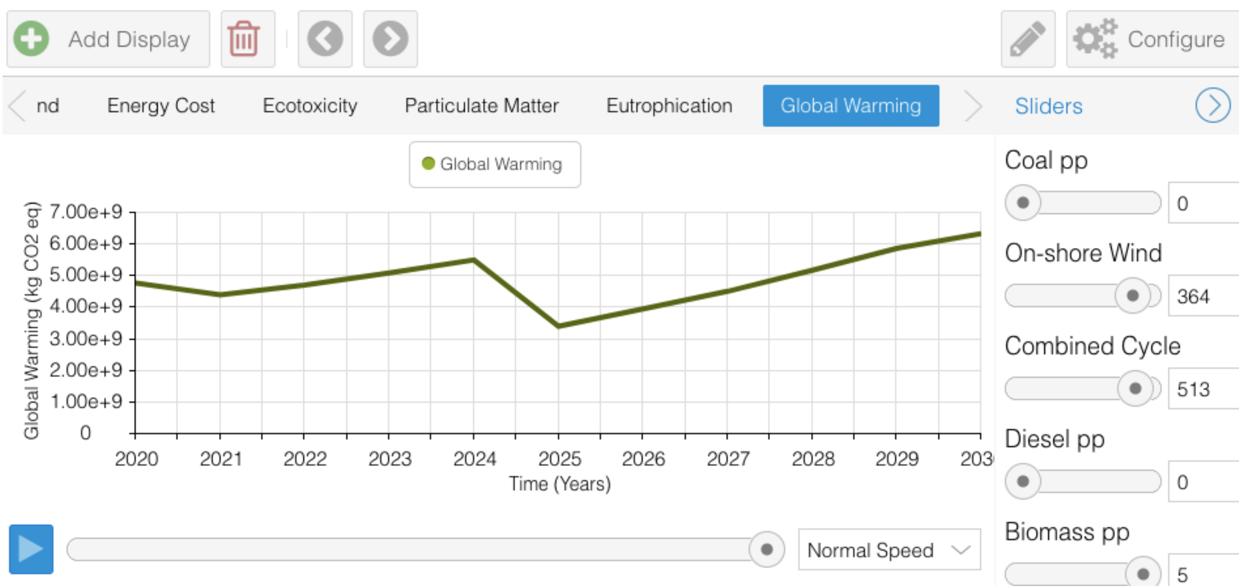

Figure 6.29: Global warming, Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

Figure 6.30: Eutrophication, Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

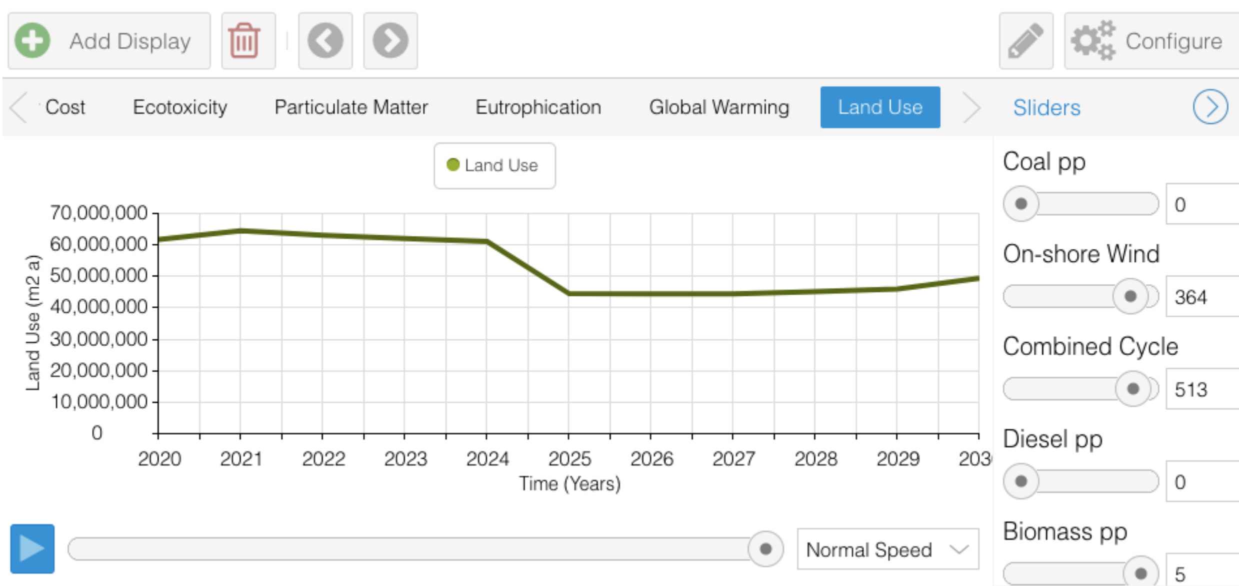

Figure 6.31: Land use, Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from diverse sources. Graphic produced in Insight Maker tool (Fortmann-Roe, S. 2014)

In relative terms, when normalized per MWh generated, it is clear that the results from this scenario are superior to those of the initial energy mix. In four out six aspects, ecotoxicity, eutrophication, global warming, and land use, final values are 50% or lower than initial values. Notably the final eutrophication value which is negligible compared to the initial case. Particulate matter was reduced by 25% of the original value and cost decreased almost 20% (see Figure 6.32). Note the ordinate axis refers to the collection of units per MWh.

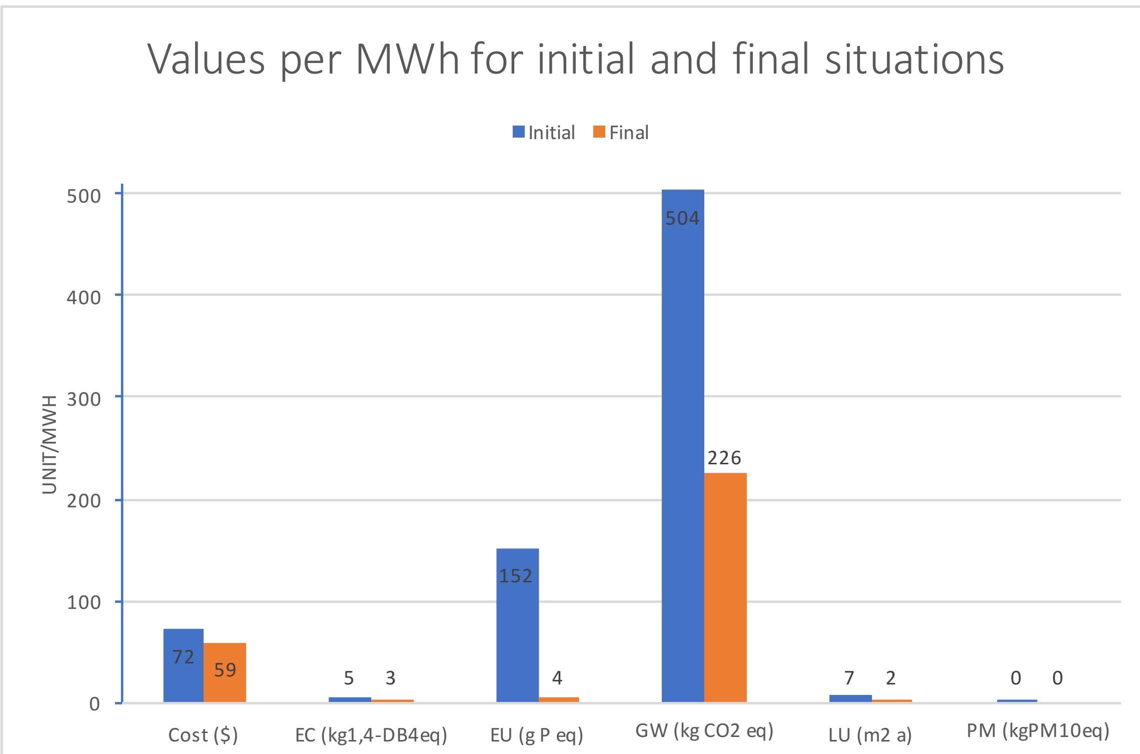

Figure 6.32: Values per MWh comparison for initial and final situations, Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from sources mentioned in text

6.5 SCENARIO COMPARISON

From the comparison of the modeled scenarios, it can be seen that scenario 2 (submarine connection) is the most capital intensive but has the best results in terms of environmental impact. Scenarios 1 (natural gas) and 4 (20/40/40) have similar costs but scenario 4 appears to have lower environmental impacts results except in the case of land use where renewables increase the value for scenario 4. Scenario 3 (50/50) presents the lowest cost while its ecotoxicity, particulate matter, and global warming values are between scenarios 1 and 4 values. Scenario 3 presents the highest values for eutrophication and land use (see Figure 6.33).

Note all figures represent values per MWh. The author decided to use these ratios instead of the absolute values because they facilitate representation. Since all the values are referred to the same generation, the absolute values proportions are preserved.

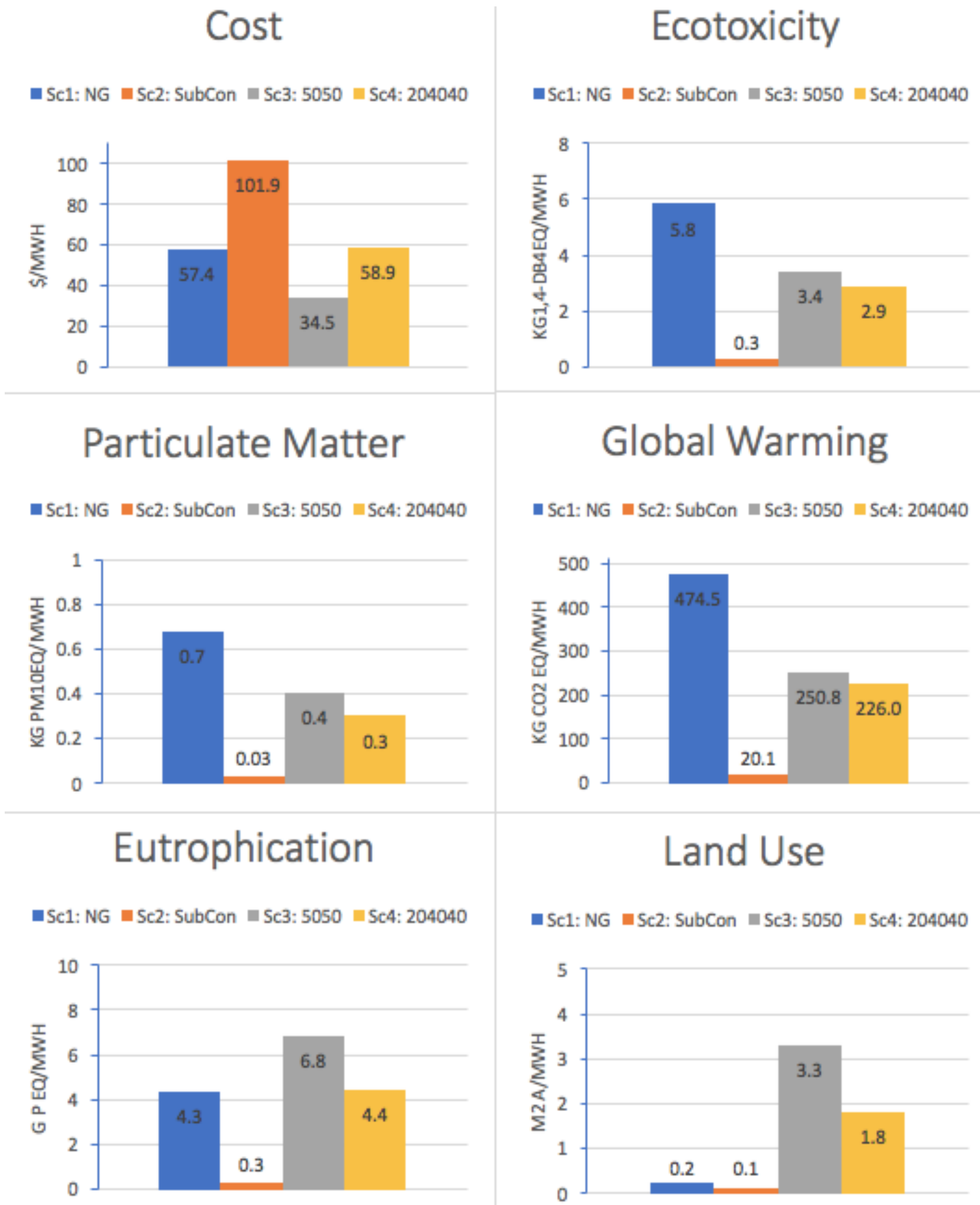

Figure 6.33: Scenario comparison results. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from sources mentioned in text

Chapter 7. Conclusions

After going through the process of completing each of the steps established in the methodology for energy transition evaluation, it is clear that good knowledge of the energy panorama at the national and regional levels including demand and generation behavior, energy infrastructure, energy market, the country's energy commodity imports, and the legislation context (current and future expectations) is very important and impacts the rest of the evaluation, the selection of scenarios, and the results. In addition, the initial resource evaluation helps to narrow down the applicable energy resources for a certain location. Finally, the scenario strategy provides a general idea of the economic and environmental consequences of different quantitative and qualitative approaches in energy transition. Consequently, the methodology can be applied to any location but the results and the conclusions will be unique to the location under study. Possible future work could include the use of other approaches such as optimization, and their comparison to the proposed methodology in this document. In addition, qualitative tools like Mental Modeler could also be applied as an alternative to Insight Maker.

For the Balearic Islands case study, the initial energy resource selection is constrained by very restrictive environmental regulation that could be relaxed to allow other renewable resources. For instance, a review of the Spanish environmental impact assessment regarding the restricted area could find potential exceptions to develop offshore wind. A new modification of the Plan Director Sectorial could consider Deep Offshore wind to facilitate its development in the future. A review of the inland environmental limitations could allow the construction of a reversible hydro power plant between Cuber and Gorg Blau dams reproducing Canary Islands strategy with Soria-Chira installation. In addition, further studies of certain technologies should be considered to provide more accurate background information, refining the final results of the study. For example, simulations in northern Menorca to test the potential of a wave power installation and deeper analysis of the Balearic thermohaline current could be carried out in order to collect data about velocity, depth, and proximity to the coast. In-depth study of biomass potential to stop relying on national data. Lastly, research in microhydro to improve the technology and make it cost effective.

In terms of the presented scenarios, significant observations can be made. From the comparison of the proposed final energy mixes with the current situation, it can be deduced that coal and diesel have higher environmental impact, especially in the case of eutrophication. Higher percentages of renewable resources do not result in the lowest environmental impact for all parameters compared to the proposed scenarios. Land use in the 50/50 scenario represents 33% of the Balearic urban land (Servicio de Información Territorial de las Islas Baleares, 2018) raising questions about the ability of the archipelago to support large renewable contributions. The same scenario presents high associated eutrophication values that may be caused by the leakage of eutrophying substances from copper mining. For scenarios where natural gas plays a main role, energy security issues must be studied carefully. Finally, the submarine connection expansion has the lowest environmental impact because pollution is shifted to the mainland. However, this strategy would only require a 2% increase in the peninsular generation but could be subject to lack of funding for the project or to rejection from pro-independence sectors of the population. Thus, a more diverse energy mix reduces the disadvantages of a one-technology focus approach.

In conclusion, every approach has its advantages and disadvantages. This methodology for energy transition evaluation helps to systematically identify these and, should be considered in technical and strategic analysis.

Appendices

A. Energy Resources Description

Potential Energy Resources		Viability
Peninsular Energy Mix	Nuclear power	No. Legislation restriction (Plan Director Sectorial, 2015)
	Coal power plants	Yes. Already present in the Balearic Islands Energy Mix
	Gas turbines	Yes. Already present in the Balearic Islands Energy Mix
	Combined cycle	Yes. Already present in the Balearic Islands Energy Mix
	Cogeneration	Yes. Already present in the Balearic Islands Energy Mix
	Hydro pure pumping	No. Conventional hydroelectric power not viable
	Waste	Yes. Already present in the Balearic Islands Energy Mix
	Conventional hydro	No. Lack of hydro resources and presence of protected areas
	Hydro mixed pumping (conventional + pumping)	No. Conventional hydroelectric power not viable
	Biomass	Yes. Limited to 10 MW
	Geothermal	No. Limited to thermal uses
	Marine hydro	Considered separately as wave, tidal, and current
	On-shore wind	Yes. Potential to grow (Plan Director Sectorial, 2015)
	Renewables waste (50% of waste)	Yes. Already present in the Balearic Islands Energy Mix
	Solar photovoltaic installations	Yes. Potential to grow (Plan Director Sectorial, 2015)
	Concentrating solar thermal	Yes. Directions to be developed on (Plan Director Sectorial, 2015)
	Biogas	No. Certain potential on mixed use with NG
Balearic Islands Current Energy Mix	Coal power plant	Yes. Already present in the Balearic Islands Energy Mix
	Diesel plants	Yes. Already present in the Balearic Islands Energy Mix
	Gas turbines	Yes. Already present in the Balearic Islands Energy Mix
	Combined cycle	Yes. Already present in the Balearic Islands Energy Mix
	Auxiliar generation	No. Avoiding emergency auxiliar generation is a must
	Cogeneration	Yes. Already present in the Balearic Islands Energy Mix
	Waste	Yes. Already present in the Balearic Islands Energy Mix
	On-shore wind	Yes. Potential to grow (Plan Director Sectorial, 2015)
	Solar photovoltaic installations	Yes. Potential to grow (Plan Director Sectorial, 2015)
	Renewable waste (50% of waste)	Yes. Already present in the Balearic Islands Energy Mix
	Biogas	No. Certain potential on mixed use with NG
Balearic Islands Desirable Energy Mix	Distributed solar photovoltaic	Yes. Directions to be developed on (Plan Director Sectorial, 2015)
	Solar photovoltaic installations	Yes. Potential to grow (Plan Director Sectorial, 2015)
	Microwind power	Yes. Directions to be developed on (Plan Director Sectorial, 2015)
	On-shore wind	Yes. Potential to grow (Plan Director Sectorial, 2015)
	Concentrating solar thermal	Yes. Directions to be developed on (Plan Director Sectorial, 2015)
	Hybrid solar photovoltaic/thermal	Yes. Directions to be developed on (Plan Director Sectorial, 2015)
Author suggestions	Off-shore wind	No. Technically viable but present environmental constraints (Spanish Strategic Environmental Assessment)
	Concentrating solar photovoltaic	Yes. Not specifically mentioned but could be included as part of the solar strategy
	Ocean wave	No. Lack of potential in the Mediterranean sea
	Tidal range	No. Lack of potential in the Mediterranean sea
	Tidal/oceanic current	No. Technical and environmental constraints
	Hydrowind	No. Conventional hydroelectric power not viable

Table A.1: Energy Mix. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

B. Energy Resources Evaluation

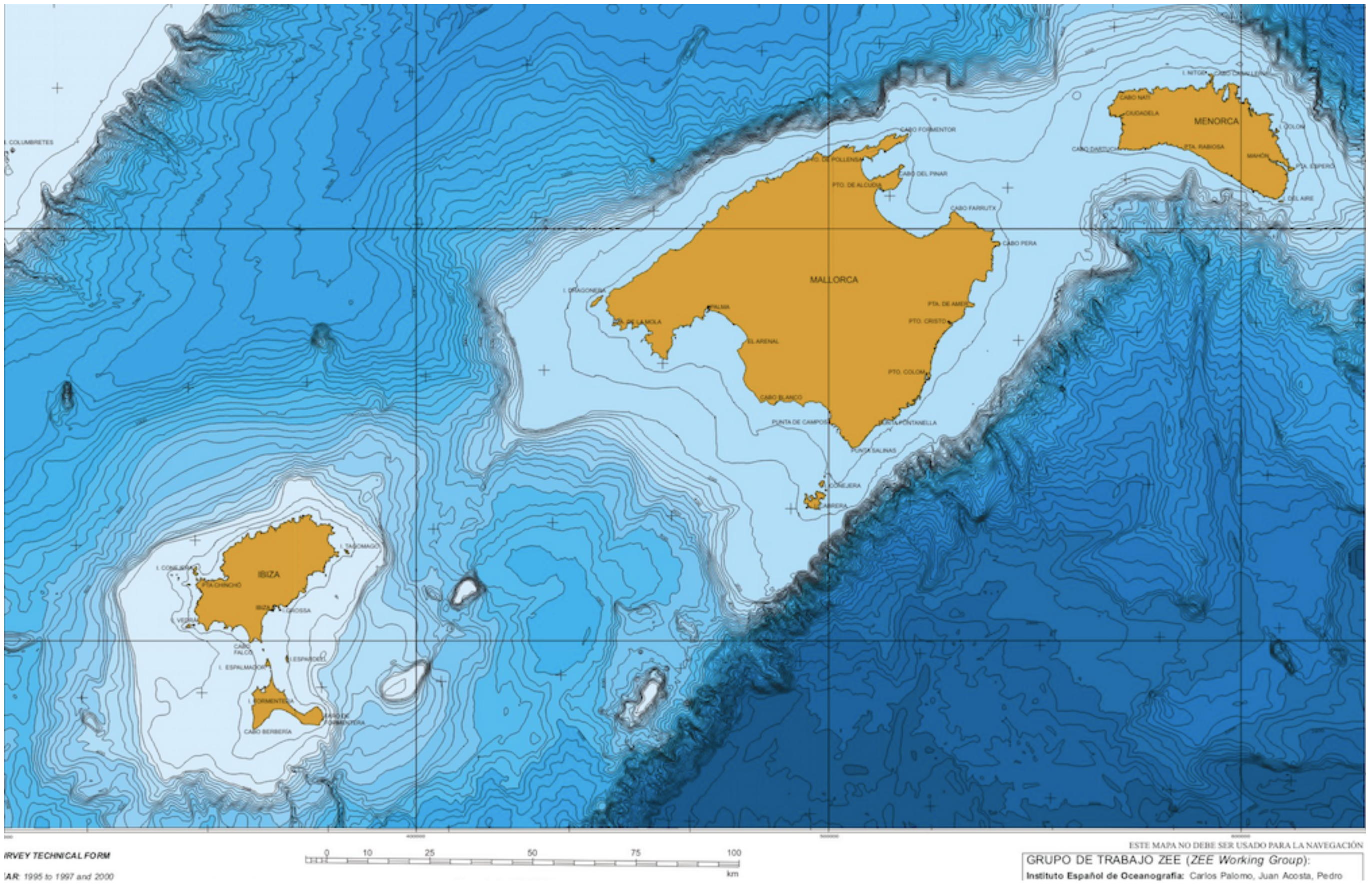

Figure B.1: Bathymetric Map of Balearic Sea and Gulf of Valencia, Western Mediterranean (Instituto Español de Oceanografía, 2001)

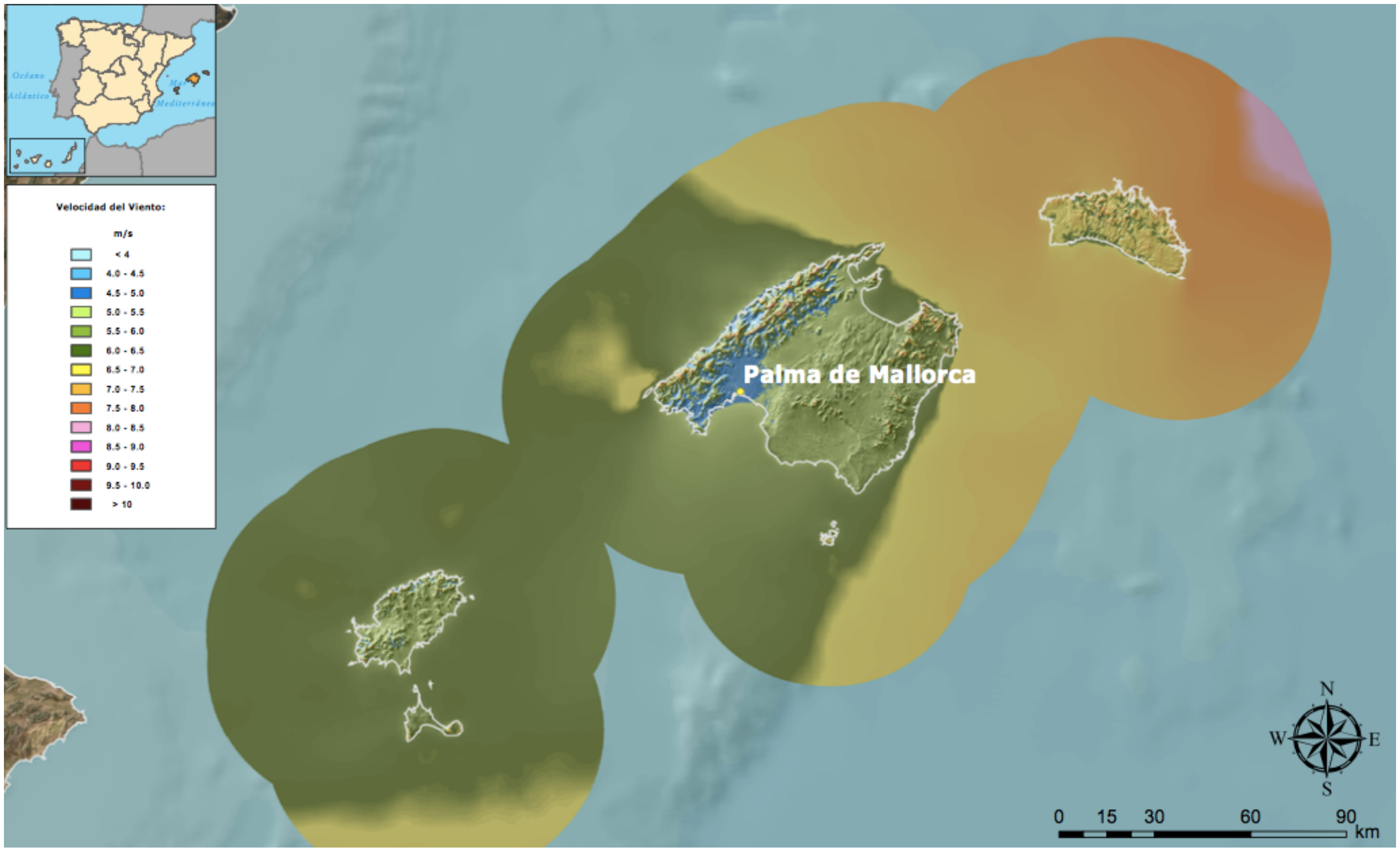

Figure B.2: Wind speed map of the Balearic Islands for 80 m height (Truewind, 2009)

C. Scenario data sets

	# units										
Technology	*Year 0*	*Year 1*	*Year 2*	*Year 3*	*Year 4*	*Year 5*	*Year 6*	*Year 7*	*Year 8*	*Year 9*	*Year 10*
Coal	11	10	9	8	7	6	5	4	3	2	0
Diesel	57	51	45	39	33	27	21	15	9	3	0
NG turbines	7	7	7	7	7	7	7	7	7	7	7
Combined Cycle	141	214	291	378	469	569	678	788	910	1037	1169
Cogeneration	24	24	24	24	24	24	24	24	24	24	24
Waste	12	12	12	12	12	12	12	12	12	12	12
On-shore wind	3	3	3	3	3	3	3	3	3	3	3
Solar PV	116	116	116	116	116	116	116	116	116	116	116
Submarine	3	3	3	3	3	3	3	3	3	3	3

Demand (MWh)	9,424,000	10,649,338	11,968,972	13,477,302	15,079,818	16,871,142	18,851,055	20,831,082	23,093,989	25,451,285	27,902,965
	Demand Increment	1,225,338	1,319,634	1,508,330	1,602,517	1,791,323	1,979,914	1,980,026	2,262,907	2,357,296	2,451,680
Generation	From coal/diesel per year (MWh)	313,536	313,536	313,536	313,536	313,536	313,536	313,536	313,536	313,536	313,536
	From coal/diesel per year (# unit)	73	78	87	91	100	109	109	123	127	132

Table C.1: Insight Maker generation input data. Scenario 1. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

First calculation

	# units										
Technology	*Year 0*	*Year 1*	*Year 2*	*Year 3*	*Year 4*	*Year 5*	*Year 6*	*Year 7*	*Year 8*	*Year 9*	*Year 10*
Coal	11	19	28	38	49	0	4	9	14	19	0
Diesel	57	72	88	106	126	0	24	49	76	105	0
NG turbines	7	7	7	7	7	7	7	7	7	7	7
Combined Cycle	141	160	181	205	230	0	31	63	99	136	0
Cogeneration	24	24	24	24	24	24	24	24	24	24	24
Waste	12	12	12	12	12	12	12	12	12	12	12
On-shore wind	3	3	3	3	3	3	3	3	3	3	3
Solar PV	116	116	116	116	116	116	116	116	116	116	116
Submarine connection	3	3	3	3	3	17	17	17	17	17	30

Demand (MWh)	9,424,000	10,649,338	11,968,972	13,477,302	15,079,818	16,871,142	18,851,055	20,831,082	23,093,989	25,451,285	27,902,965
	Increment	1,225,338	1,319,634	1,508,330	1,602,517	1,791,323	1,979,914	1,980,026	2,262,907	2,357,296	2,451,680
Generation (MWh)	Coal	408,446	439,878	502,777	534,172		659,971	660,009	754,302	785,765	
	Diesel	408,446	439,878	502,777	534,172		659,971	660,009	754,302	785,765	
	CC	408,446	439,878	502,777	534,172		659,971	660,009	754,302	785,765	
Generation (#unit)	Coal	8	9	10	11		4	4	5	5	
	Diesel	15	16	19	20		24	24	28	29	
	CC	19	21	24	25		31	31	36	37	

Sub Connection	MWh	#units
Supplied by constants	1,713,283	
Rest in year 5	15,157,858	17
Rest in year 10	26,189,682	30

Final results from iteration

	# units										
Technology	*Year 0*	*Year 1*	*Year 2*	*Year 3*	*Year 4*	*Year 5*	*Year 6*	*Year 7*	*Year 8*	*Year 9*	*Year 10*
Coal	11	16	23	31	39	0	0	5	10	15	0
Diesel	57	56	61	68	74	0	35	58	86	116	0
NG turbines	7	7	7	7	7	7	7	7	7	7	7
Combined Cycle	141	140	147	155	163	0	45	75	112	150	0
Cogeneration	24	24	24	24	24	24	24	24	24	24	24
Waste	12	12	12	12	12	12	12	12	12	12	12
On-shore wind	3	3	3	3	3	3	3	3	3	3	3
Solar PV	116	116	116	116	116	116	116	116	116	116	116
Submarine connectior	3	3	3	3	3	18	18	18	18	18	30

Table C.2: Insight Maker generation input data. Scenario 2. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

First calculation

	# units										
Technology	*Year 0*	*Year 1*	*Year 2*	*Year 3*	*Year 4*	*Year 5*	*Year 6*	*Year 7*	*Year 8*	*Year 9*	*Year 10*
Coal	11	10	9	8	7	6	5	4	3	2	0
Diesel	57	51	45	39	33	27	21	15	9	3	0
NG turbines	7	7	7	7	7	7	7	7	7	7	7
Combined Cycle	141	98	133	173	216	264	317	370	431	494	561
Cogeneration	24	24	24	24	24	24	24	24	24	24	24
Waste	12	12	12	12	12	12	12	12	12	12	12
On-shore wind	3	141	191	249	310	379	454	530	616	706	803
Solar PV	116	215	292	380	473	578	693	809	941	1078	1225
Submarine connection	3	3	3	3	3	3	3	3	3	3	3
Biomass	0	5	5	5	5	5	5	5	5	5	5
Microwind	0	46,919	63,727	82,940	103,352	126,168	151,387	176,608	205,431	235,457	267,522
Distributed Solar PV	0	107,419	145,902	189,888	236,621	288,859	346,597	404,339	470,330	539,073	612,485
Hybrid Solar thermal/PV	0	30,691	41,686	54,254	67,606	82,531	99,028	115,525	134,380	154,021	174,996
CSPV	0	8,594	11,672	15,191	18,930	23,109	27,728	32,347	37,626	43,126	48,999
CST	0	33	44	58	72	88	105	123	143	164	186

Demand (MWh)		9,424,000	10,649,338	11,968,972	13,477,302	15,079,818	16,871,142	18,851,055	20,831,082	23,093,989	25,451,285	27,902,965
Generation (MWh)	Supplied by constants	4,140,552	4,140,552	4,140,552	4,140,552	4,140,552	4,140,552	4,140,552	4,140,552	4,140,552	4,140,552	4,140,552
	From coal and diesel	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365
	Substraction		3,373,422	4,693,055	6,201,385	7,803,902	9,595,225	11,575,138	13,555,165	15,818,072	18,175,368	20,627,048
	Coal replacement		147,168	147,168	147,168	147,168	147,168	147,168	147,168	147,168	147,168	294,336
	Diesel replacement		162,936	162,936	162,936	162,936	162,936	162,936	162,936	162,936	162,936	81,468
	Total to cover		3,683,526	5,003,159	6,511,489	8,114,006	9,905,329	11,885,242	13,865,269	16,128,176	18,485,472	21,002,852
	CC		1,841,763	2,501,580	3,255,744	4,057,003	4,952,664	5,942,621	6,932,634	8,064,088	9,242,736	10,501,426
	Renewables		1,841,763	2,501,580	3,255,744	4,057,003	4,952,664	5,942,621	6,932,634	8,064,088	9,242,736	10,501,426
		1/8	230,220	312,697	406,968	507,125	619,083	742,828	866,579	1,008,011	1,155,342	1,312,678
	10MW of biomass	20,148										
		Extra from biomass	210,072	292,549	386,820	486,977	598,935	722,680	846,431	987,863	1,135,194	1,292,530

Demand (MWh)	Increment	1,225,338	1,319,634	1,508,330	1,602,517	1,791,323	1,979,914	1,980,026	2,262,907	2,357,296	2,451,680
Generation	From coal/diesel per year (MWh)	313,536	313,536	313,536	313,536	313,536	313,536	313,536	313,536	313,536	313,536
	From coal/diesel per year (# unit)	73	78	87	91	100	109	109	123	127	132

Final results from iteration

	# units										
Technology	*Year 0*	*Year 1*	*Year 2*	*Year 3*	*Year 4*	*Year 5*	*Year 6*	*Year 7*	*Year 8*	*Year 9*	*Year 10*
Coal	11	10	9	8	7	6	5	4	3	2	0
Diesel	57	51	45	39	33	27	21	15	9	3	0
NG turbines	7	7	7	7	7	7	7	7	7	7	7
Combined Cycle	141	98	133	173	216	264	317	370	431	494	561
Cogeneration	24	24	24	24	24	24	24	24	24	24	24
Waste	12	12	12	12	12	12	12	12	12	12	12
On-shore wind	3	117	168	223	280	341	407	473	546	621	701
Solar PV	116	179	257	340	427	520	622	722	833	948	1070
Submarine connection	3	3	3	3	3	3	3	3	3	3	3
Biomass	0	5	5	5	5	5	5	5	5	5	5
Microwind	0	39153	56072	74247	93221	113629	135827	157745	181970	207140	233757
Distributed Solar PV	0	89640	128376	169987	213427	260150	310973	361152	416616	474241	535181
Hybrid Solar thermal/PV	0	25612	36679	48568	60979	74328	88849	103186	119033	135497	152909
CSPV	0	7171	10270	13599	17074	20812	24878	28892	33329	37939	42815
CST	0	27	39	52	65	79	95	110	127	144	163

Table C.3: Insight Maker generation input data. Scenario 3. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

First calculation

Technology	# units Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Coal	11	10	9	8	7	6	5	4	3	2	0
Diesel	57	51	45	39	33	27	21	15	9	3	0
NG turbines	7	7	7	7	7	7	7	7	7	7	7
Combined Cycle	141	115	159	209	262	88	154	220	295	373	434
Cogeneration	24	24	24	24	24	24	24	24	24	24	24
Waste	12	12	12	12	12	12	12	12	12	12	12
On-shore wind	3	70	92	118	145	56	90	123	161	201	271
Solar PV	116	107	141	180	221	86	137	188	246	307	413
Submarine connection	3	3	3	3	3	11	11	11	11	11	11
Biomass	0	5	5	5	5	5	5	5	5	5	5
Microwind	0	23,368	30,788	39,270	48,282	18,767	29,901	41,035	53,760	67,016	90,234
Distributed Solar PV	0	53,500	70,489	89,909	110,540	42,966	68,457	93,949	123,083	153,432	206,588
Hybrid Solar thermal/PV	0	15,286	20,140	25,688	31,583	12,276	19,559	26,843	35,167	43,838	59,025
CSPV	0	4,280	5,639	7,193	8,843	3,437	5,477	7,516	9,847	12,275	16,527
CST	0	16	21	27	34	13	21	29	37	47	63

Demand (MWh)		9,424,000	10,649,338	11,968,972	13,477,302	15,079,818	16,871,142	18,851,055	20,831,082	23,093,989	25,451,285	27,902,965
Generation (MWh)	Supplied by constants	1,512,552	1,512,552	1,512,552	1,512,552	1,512,552	1,512,552	1,512,552	1,512,552	1,512,552	1,512,552	1,512,552
	Supplied by NG turbines	539,053	539,053	539,053	539,053	539,053	539,053	539,053	539,053	539,053	539,053	539,053
	From coal and diesel	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365	3,135,365
	Substraction		6,001,422	7,321,055	8,829,385	10,431,902	12,223,225	14,203,138	16,183,165	18,446,072	20,803,368	23,255,048
	Coal replacement		147,168	147,168	147,168	147,168	147,168	147,168	147,168	147,168	147,168	294,336
	Diesel replacement		162,936	162,936	162,936	162,936	162,936	162,936	162,936	162,936	162,936	81,468
	Total to cover		6,850,578	8,170,212	9,678,542	11,281,058	13,072,382	15,052,295	17,032,322	19,295,229	21,652,525	24,169,905
	Submarine connection		2,628,000	2,628,000	2,628,000	2,628,000	9,667,962	9,667,962	9,667,962	9,667,962	9,667,962	9,667,962
	Substraction		4,222,578	5,542,212	7,050,542	8,653,058	3,404,420	5,384,333	7,364,360	9,627,267	11,984,563	14,501,943
	CC		2,955,805	3,879,548	4,935,379	6,057,141	2,383,094	3,769,033	5,155,052	6,739,087	8,389,194	9,667,962
	Renewables		1,266,774	1,662,664	2,115,162	2,595,918	1,021,326	1,615,300	2,209,308	2,888,180	3,595,369	4,833,981
		0	158,347	207,833	264,395	324,490	127,666	201,912	276,163	361,023	449,421	604,248
	10MW of biomass	20,148										
		Extra from biomass	138,199	187,685	244,247	304,342	107,518	181,764	256,015	340,875	429,273	584,100
		0	19,743	26,812	34,892	43,477	15,360	25,966	36,574	48,696	61,325	83,443

Final results from iteration

Technology	# units Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Coal	11	10	9	8	7	6	5	4	3	2	-
Diesel	57	51	45	39	33	27	21	15	9	3	-
NG turbines	7	7	7	7	7	7	7	7	7	7	7
Combined Cycle	141	127	178	236	296	130	203	276	359	445	513
Cogeneration	24	24	24	24	24	24	24	24	24	24	24
Waste	12	12	12	12	12	12	12	12	12	12	12
On-shore wind	3	84	115	149	185	106	148	190	237	286	364
Solar PV	116	128	175	228	282	161	225	290	362	436	555
Submarine connection	3	3	3	3	3	11	11	11	11	11	11
Biomass	-	5	5	5	5	5	5	5	5	5	5
Microwind	-	27,984	38,322	49,728	61,647	35,244	49,228	63,238	79,034	95,203	121,305
Distributed Solar PV	-	64,069	87,737	113,851	141,138	80,690	112,707	144,782	180,946	217,964	277,725
Hybrid Solar thermal/PV	-	18,305	25,068	32,529	40,325	23,054	32,202	41,366	51,699	62,275	79,350
CSPV	-	5,125	7,019	9,108	11,291	6,455	9,017	11,583	14,476	17,437	22,218
CST	-	19	27	35	43	25	34	44	55	66	84

Table C.4: Insight Maker generation input data. Scenario 4. Source: created by Henar Rabadan Perucha at The University of Texas at Austin with data from El sistema eléctrico español Informe 2016 (REE, 2016)

Glossary

CCS – Carbon Capture and Storage

CFC – ChloroFluoroCarbons

DB - DichloroBenzene

EEA - European Environment Agency

EMAYA - Empresa Municipal de Aguas y Alcantarillado

EU – European Union

EV – Electric Vehicle

EWEA – European Wind Energy Association

GHG – GreenHouse Gas

GWP – Global Warming Potential

IDAE – Instituto para la Diversificación y Ahorro de la Energía

IEA – International Energy Agency

IGME – Instituto Geológico Minero de España

IGN – Instituto Geográfico Nacional

INE – Instituto Nacional de Estadística

LCA – Life Cycle Assessment

MARM - Ministerio de Medio Ambiente, Medio Rural y Marino de España

NG – Natural Gas

NGCC – Natural Gas Combined Cycle

NREL - National Renewable Energy Laboratory

OECD - Organisation for Economic Co-operation and Development

P - Phosphorous

PER – Plan de Energías Renovables

PNAS – Proceeding of the National Academy of Sciences of the United States of America

PV – PhotoVoltaic

REE – Red Eléctrica de España

SCPC - Supercritical Pulverized Coal

SEIA - Solar Energy Industries Association

WEC - Wave Energy Converter

Bibliography

Álvarez Llabre, F. 2014. Microhydroelectric power plant of 50 MW in Mallorca, Spain.

Arrizabalaga, I. et al. 2015. Country Update for the Spanish Geothermal Sector.

Biomass Power Association 2017. US Biomass Power Facilities [Online] Available at: http://www.usabiomass.org/docs/biomass_map.pdf [Accessed 05 December 2017].

Cabrera Bonet, M. 2013. La biomasa en España. Disponibilidad de recursos PER 2011-2020.

Colmenar-Santos, A. et al. 2015. The geothermal potential in Spain.

Council of Mallorca 2011. Plan Territorial de Mallorca.

Empresa Municipal de Aguas y Alcantarillado 2017. Embalses [Online] Available at: https://www.emaya.es/es/areas/centrales/embalses [Accessed 22 October 2017].

Enair 2017. Microwind [Online] Available at: https://www.enair.es/?gclid=EAIaIQobChMI6d2exJrb1wIVxLjACh1t3gZyEAMYASAAEgL1KPD_BwE [Accessed 05 December 2017].

European Environment Agency 2016. Natura 2000 Network Viewer [Online] Available at: http://natura2000.eea.europa.eu/ [Accessed 22 October 2017].

European Union 2009. Official Journal of the European Union, European Directive 2009/28/EC.

European Wind Energy Association 2013. Deep water: The next step for offshore wind energy. Brussels: EWEA publications.

Exceltur 2014. Estudio del impacto económico del turismo sobre la economía y el empleo de las islas Baleares, Impactur 2014.

Ezzati, M. et al 2004. Comparative Quantification of Health Risks: Global and Regional Burden of Diseases Attributable to Selected Major Risk Factors. Geneva: World Health Organization publications.

Fortmann-Roe, S. 2014. Insight Maker: A general-purpose tool for web-based modeling & simulation. Elsevier publications.

Fraenkel, P.L. 2002. Power from marine currents.

Gobierno de España 2014. Portal de la transparencia [Online] Available at: http://transparencia.gob.es/servicios-buscador/contenido/conveniosyencomiendas.htm?id=Convenio_IET201400027&fcAct=2017-09-20T12:20:34.635Z&lang=ca-valencia [Accessed 05 December 2017].

Gobierno de las Islas Baleares 2007. Boletín Oficial de las Islas Baleares num. 54 EXT. Palma: Boletín Oficial de las Islas Baleares.

Gobierno de las Islas Baleares 2010. La población de las islas Baleares. Palma: Gobierno de Islas Baleares publications.

Gobierno de las Islas Baleares 2015. Boletín Oficial de las Islas Baleares, Decree 33/2015.

Gobierno de las Islas Baleares 2015. Energías Renovables y Eficiencia Energética en las Islas Baleares: Estrategias y líneas de actuación. Palma: Gobierno de Islas Baleares publications.

Gobierno de las Islas Baleares 2015. Plan Director Sectorial Energético de las Illes Balears. Palma: Boletín Oficial de las Islas Baleares.

Gobierno de las Islas Baleares 2015. Plan Hidrológico de las Islas Baleares. Palma: Gobierno de Islas Baleares publications.

Gobierno de las Islas Baleares 2017. El turismo en las Islas Baleares Anuario 2016. Palma: Gobierno de Islas Baleares publications.

Goedkoop, M. et al 2008. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition: Report I: Characterisation. The Hague, NL: Dutch Ministry of the Environment publications.

Hertwich, E.G. et al 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. PNAS publications.

Instituto Español de Oceanografía 2001. Bathymetric Map of Balearic Sea and Gulf of Valencia, Western Mediterranean. Madrid: Gobierno de España publications.

Instituto Geológico Nacional 2017. Cartografía y Datos Geográficos, IBERPIX tool.

Instituto Nacional de Estadística 2008. Km medios recorridos al año por los vehículos para uso personal, por comunidad autónoma de residencia y tipo de combustible - Islas Baleares y cualquier combustible [Online] Available at: http://www.ine.es/jaxi/Datos.htm?path=/t25/p500/2008/p08/l0/&file=08016.px [Accessed 20 January 2018].

Instituto Nacional de Estadítica 2016. Demografía y Población, INEbase.

Instituto para la Diversificación y Ahorro de Energía 2010. Evaluación del potencial de energía geotérmica. Estudio técnico PER 2011-2020.

Instituto para la Diversificación y Ahorro de la Energía 2011. Plan de Energías Renovables 2011-2020. Madrid: Gobierno de España publications.

Instituto para la Diversificación y Ahorro de la Energía 2011. Informe de sostenibilidad ambiental del Plan de Energías Renovables 2011-2020. Madrid: Gobierno de España publications.

International Energy Agency 2016. World Energy Outlook 2016, Executive Summary. France: IEA publications.

Ministerio de Energía, Turismo y Agenda Digital 2016. Boletín de Coyuntura Trimestral Cuarto Trimestre 2016. Gobierno de España publications.

Ministerio de Medio Ambiente, Medio Rural y Marino de España 2005. Evaluación preliminar de los Impactos en España por Efectos del Cambio Climático. Madrid: Gobierno de España publications.

National Renewable Energy Laboratory 2017. Solar photovoltaics – concentrator photovoltaics [Online] Available at: http://solareis.anl.gov/documents/docs/NREL_PV_3.pdf [Accessed 05 December 2017].

Navarro, A. et al 1993. Las aguas subterráneas en España. Madrid: IGME publications.

NuGen Engineering Ltd. 2010. Feasibility Study for a 10 MW Biomass Fired Power Plant

Ocean Energy Council 2017. Tidal energy [Online] Available at: http://www.oceanenergycouncil.com/ocean-energy/tidal-energy/ [Accessed 20 October 2017].

Patierno, M. et al 2017. Perfil de las centrales térmicas de carbón de Endesa Generación S.A en la Península Ibérica. Endesa publications.

Pelamis 2017. Pelamis Global Resource. [Online] Available at: http://www.pelamiswave.com/global-resource/ [Accessed 10 September 2017].

Ponce de León, S. et al 2015. Wave energy in the Balearic Sea. Evolution from a 29 year spectral wave hindcast. Elsevier publications.

Red Eléctrica de España 2012. Project Rómulo, interconexión eléctrica Peninsula-Baleares. Red Eléctrica de España publications.

Red Eléctrica de España 2015. El sistema eléctrico balear. Red Eléctrica de España publications.

Red Eléctrica de España 2016. El sistema eléctrico español Informe 2016. Red Eléctrica de España publications.

Red Eléctrica de España 2016. Las energías renovables en el Sistema eléctrico español. Red Eléctrica de España publications.

Retief, F. et al 2016. Global megatrends and their implications for environmental assessment practice. Elsevier publications.

Rodríguez-Rodríguez, D. et al 2016. Achieving Blue Growth through maritime spatial planning: Offshore wind energy optimization and biodiversity conservation in Spain. Elsevier publications.

Rubio Company, A. 2006. Remolinos de mesoescala en el mediterráneo noroccidental: Generación y evolución.

Servicio de Información Territotial de las Islas Baleares 2018. Detalle Geoestadísticas. Superficies de suelo rústico y de áreas de desarrollo urbano. [Online] Available at:https://www.caib.es/sacmicrofront/noticia.do?idsite=5505&cont=86264&lang=es [Accessed 17 February 2018].

Solar Energy Industries Association 2017. Concentrating Solar Power [Online] Available at: https://www.seia.org/initiatives/concentrating-solar-power [Accessed 5 December 2017].

Tablademareas 2017. Tabla de mareas y solunares de islas Baleares. [Online] Available at: http://www.tablademareas.com/es/islas-baleares [Accessed 15 September 2017].

The World Bank 2017. Population growth in Spain [Online] Available at: https://data.worldbank.org/indicator/SP.POP.GROW?contextual=default&end=2016&locations=ES&start=1960&view=chart [Accessed 05 December 2017].

Truewind 2009. Wind speed map of the Balearic Islands for 80 m height. Gobierno de España publications.

US Department of Energy 2017. Alternative Fuels Data Center [Online] Available at: https://www.afdc.energy.gov/fuels/electricity_charging_home.html [Accessed 05 December 2017].